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Massachusetts Institute of Technology

EFFECT OF HIGH EXHAUST PRESSURES ON ENGINE PERFORMANCE AND THE AVAILABILITY OF ENERGY IN EXHAUST GASES AT HIGH PRESSURES

BY

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by

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Submitted in Partial Fulfillment of the Requirements for the

Degree of

Master of Science in

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Cambridge, Massachusetts
June 10, 1944

Professor George W. Swett
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

A thesis entitled "The Effect of High Exhaust Pressures on Engine Performance and the Availability of Energy in Exhaust Gases at High Pressures" is herewith submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

Respectfully,

SYMBOLS

A	Area in square inches
B	Ratio of diameter of orifice to diameter of pipe
BHP	Brake horse power
BL	Brake load, inches of mercury
e	Volumetric efficiency
F	W_F/W_A = fuel-air ratio
H	Orifice pressure drop, inches of alcohol
hi	Gage manifold pressure, inches of mercury
he	Gage exhaust pressure, inches of mercury
I_{ex}	Exciter current, amperes
K	Orifice coefficient
ℓ	Stroke in inches
L	Brake arm length in inches
m.e.p.	Mean effective pressure, p.s.i.
b.m.e.p.	Brake mean effective pressure, p.s.i.
f.m.e.p.	Friction mean effective pressure, p.s.i.
i.m.e.p.	Indicated mean effective pressure, p.s.i.
p.m.e.p.	Pumping mean effective pressure, p.s.i.
N	Revolutions per minute
P	Pressure ahead of orifice, inches of mercury, equal to P_1 plus corrected barometric pressure
P_1	Gage pressure ahead of orifice, inches of mercury
P_e	Exhaust pressure, inches of mercury
P_i	Inlet (manifold) pressure, inches of mercury
Rot.	Rotameter reading

S.A.	Spark advance in degrees before top dead center
T	Temperature of air entering orifice in degrees Rankine
T_i	Inlet (manifold) temperature, degrees Rankine
T_1, T_2, T_3	Temperatures measured in calorimeter, degrees F.
T_4	Temperature in exhaust pipe, degrees F.
W_A	Mass rate of airflow, pounds per hour
W_F	Mass rate of fuel flow, pounds per hour
Y	Expansion factor

SUMMARY

The purpose of this investigation was to determine the effects of exhaust back pressure on engine operation and to predict the influence of increasing back pressures on a composite aircraft power plant that may be typical of those to come in the near future.

A Lycoming single-cylinder engine was used for the investigation, and all of the work was performed in the Sloan Engine Laboratory at M. I. T.

During the conduct of the test runs the engine was operated at a piston speed of 3000 feet per minute with a fuel-air ratio of 0.080, spark advance of 28 degrees, manifold inlet air temperature of 140 degrees F., and all other variables were maintained essentially constant.

Exhaust pressure was varied from 30 to 60 inches of Hg. in 10-inch increments, and manifold pressure was varied from 30 to 50 inches of mercury in the same increments for each exhaust pressure. Sufficient data was recorded to plot a map of the region under investigation.

The results of the work pointed out certain well-defined conclusions which may be stated as follows:

1. The Mass Rate of Air Flow, Volumetric Efficiency, i.m.e.p., b.m.e.p., and B.H.P. all decrease with increasing exhaust back pressure.

2. The volumetric efficiency is a linear function of P_e/P_i and it decreases with increase in that pressure ratio.

3. The exhaust manifold temperature seems to increase with increase in exhaust pressure independently of inlet manifold pressure, but as distance from the cylinder increases the temperature drops off considerably with increase in exhaust pressure, and the effect is greatest at the lower values of inlet manifold pressure.

4. The maximum net power output of a CET system can be obtained by operating at an exhaust pressure substantially higher than atmospheric pressure and at a value of P_e/P_i of from 0.8 to 1.0.

INTRODUCTION

The ever increasing demands made by the operators of both commercial and military aircraft for greater speeds and higher altitudes have been reflected in the design of high output aircraft engines. The most common means today of increasing output is through the use of both gear driven and turbo superchargers, but recently jet propulsion has entered the field and it is to be expected that the gas turbine will also be applied to aeronautical power plants.

These trends have served to focus attention on a most important variable that heretofore has not received a place of primary importance and the data collected on it has been inadequate. That variable is exhaust back pressure.

It was the purpose of this investigation to explore the effects of exhaust back pressure over a sufficiently wide range in order to determine its effect on engine operation and also to predict its influence on the power output of a power plant combination that may be typical of future aircraft power plants.

DESCRIPTION OF APPARATUS

The engine used for this investigation was a single cylinder "Bore-Stroke Ratio" Lycoming test engine. It was liquid-cooled with dual spark ignition, single inlet and exhaust valves, compression ratio of 6, bore 5.25", and stroke 6.25".

General Description

Figure A shows a diagramatic setup of the apparatus.

The power output was absorbed by a Reliance Eddy Current Dynamometer. The brake load was measured by a hydraulic scale sometimes referred to as a torque cell. Calibration of the brake was previously made. Readings were taken by using a mercury manometer where the height of the mercury column was interpreted to give b.m.e.p. or BHP according to the choice of constants. A check of the zero reading was made before and after each run.

The speed of the engine was kept constant for the investigation by varying the engine output. The speed was determined by a tachometer and a 60-cycle stroboscopic light directed on a pattern disc on the flywheel.

Spark control was accomplished by the conventional type spark disc.

Intake air was supplied by laboratory compressors and the control of flow to the induction line was accomplished by the use of a Minneapolis Honeywell gate valve which bled to atmosphere. The air was metered in the induction line by means of a sharp-edged orifice with an alcohol manometer to measure pressure drop. Orifice pressure as well as surge tank temperature was measured by a Bureau of Standards iron constant thermocouple and a Tagliabu Potentiometer. Mass rate of airflow

was thereby determined.

One hundred octane fuel was supplied to the induction line after the air orifice. The mixture then entered the vaporizing and surge tank where it was kept at constant temperature by regulating the amount of steam to the jacket. The rate of fuel flow was determined by a Fischer and Porter Stabl-Vis Rotameter.

The water brake, valve gear, ignition breaker points, and tachometer were driven by the engine crankshaft. All other accessories were driven by a three-phase induction motor which was also used for starting.

Oil temperature was controlled by water through a heat exchanger and stabilized in a large tank. Cylinder temperature was controlled by regulating water flow through the cylinder jacket.

Records of cylinder pressure versus crank angle were taken with the M.I.T. High Speed Engine Indicator. P-V diagrams were drawn from these records.

Special Equipment

In order to get representative temperatures of the exhaust gases from the engine under various back pressures, a calorimeter as indicated in Figure B was constructed. Basically the calorimeter is a shell within a shell arrangement with baffles designed to retard heat losses from the center where three shielded Chromel-Alumel thermocouples were installed for the purpose of measuring the temperature of representative samples of gas. One additional Platinum-Iridium thermocouple was installed in the exhaust stack that coupled the engine to the calorimeter. A mercury manometer was connected to a tap in the

calorimeter for the purpose of measuring the exhaust pressure.

From the calorimeter the exhaust gases were led to a surge tank, where they were partially cooled by water and exhausted through a Minneapolis Honeywell valve which was used to control the back pressure. The bleed from the calorimeter jacket was used as necessary for minor adjustments in exhaust pressure.

PROCEDURE

The purpose of this investigation was to determine the effect of high back pressure on engine performance. Exhaust pressure was the main independent variable and manifold pressure the secondary independent variable. All other variables were maintained as near as possible to the following values:

Piston Speed	= 3000 Ft./Min. (2884 R.P.M.)
F	= .0800 $\pm$ .0010
T_i	= 140 $\pm$ 1° F.
S. A.	= 28° (Dual spark plugs)
	= 35° (Single spark plug operation during taking of indicator cards)

The engine was operated on 100 octane gasoline and the operating temperatures and pressures didn't vary substantially from the following values:

Oil Pressure	58-70 pounds per square inch
Cylinder Oil Pressure	55-65 pounds per square inch
Inlet Oil Temperature	150° F.
Cylinder Temperature	175-185° F.

Several familiarization runs were made in order to determine the optimum method of starting the engine and coming up to speed and equilibrium. The F, T_i and S. A. were determined during these runs and the values listed above decided upon as those to be used for the conduct of the investigation.

The value of 140° for T_i was believed to be representative of the temperature found in the inlet manifold of a supercharged engine

and the investigation presupposes that this information will be applied only to supercharged engines or power plants using an air compressor as part of the equipment.

During the familiarization period runs were taken at high and low values of inlet and exhaust pressure, in order to determine the temperature, pressure, and velocity effects on the installation and procedure.

Record runs for obtaining test data were made at the following values of exhaust pressure and inlet pressure in order to obtain sufficient data to plot a map covering the desired region.

Inlet Pressure "Hg.	Exhaust Pressure "Hg.
30	30
30	40
30	50
30	60
40	30
40	40
40	50
40	60
50	30
50	40
50	50
50	60

The number of runs made at each of these pressure combinations varied from one to nine, and the small numeral opposite the points on the enclosed curves is an indication of the number taken at that particular pressure combination.

Indicator cards were taken to determine the i.m.e.p. and p.m.e.p. of the engine and the points chosen for these determinations were as follows:

Inlet Pressure "Hg.	Exhaust Pressure "Hg.
30	40
40	30
40	40
40	50
40	60
50	40

The M.I.T. indicator card apparatus was used, and as this is the type that gives a curve of crank angle vs pressure, the cards had to be converted to the pressure-volume type with the aid of the auxiliary apparatus. A planimeter was then used to determine the areas of the cards to get the m.e.p.'s.

Both heavy and light spring (150 and 5 p.s.i./inch) cards were taken,as it was desired to know the value of the pumping loop quite accurately in order to get a picture of the effect of back pressure on the P.M.E.P.

During all of the runs sufficient data was recorded to compute the volumetric efficiency, b.m.e.p. and B.H.P. Exhaust temperatures were recorded by means of thermocouples. For the actual data recorded the reader is referred to Appendix A, which is a summarized data sheet for all runs where the fuel-air ratio was maintained within 1.25%. The data sheets for all runs are on record in the files of the M.I.T. Aero. Engine Laboratory.

Both Platinum-Iridium and Chromel-Alumel thermocouples were used in the exhaust manifold at various times during the test. The Platinum-Iridium was used first, as it was not known what temperatures would be encountered in the manifold; but after the test was underway the Chromel-Alumel couple was used to replace the Platinum-Iridium couple when the latter failed. Chromel-Alumel couples were used exclu-

sively in the calorimeter and the position of the couples was varied from time to time, but no error in position was evident. The thermocouples always indicated a falling temperature gradient with distance from the cylinder.

RESULTS AND DISCUSSION

For the purpose of analyzing the results of this investigation the effects of increased exhaust pressure on several dependent variables directly connected with engine performance are discussed below.

Mass Rate of Airflow

Figure 1 shows the effect of exhaust pressure on the mass rate of air flow. There is a linear reduction of airflow with increasing exhaust pressure over the range of exhaust pressures from 30 to 60 inches Hg. It is probable that this linear relationship would not exist at appreciably lower exhaust pressures or where P_e/P_i was less than the critical pressure ratio. In this lower range, when the velocity of sound is approached in the inlet ports, no increase in airflow should be expected with a further reduction of exhaust pressure.

Volumetric Efficiency

Figures 2 and 3 show the variation of volumetric efficiency with exhaust pressure for three inlet pressures. The volumetric efficiency decreases linearly with increasing exhaust pressures for each inlet pressure but when plotted against P_e there is some spread to the curves at the higher exhaust pressures. This is because the fractional increase in pressure is not uniform. In Figure 3 there is shown a constant linear decrease in volumetric efficiency with an increase of the ratio P_e/P_i. This relationship was found to be in close agreement with a theoretical relationship of volumetric efficiency to P_e/P_i which is based on the following assumptions:

1. No pressure drop through the valves
2. No heat losses
3. No heat transfer during the inlet process
4. Adiabatic expansion or contraction of the residual gases to inlet pressure before the inlet process

The theoretical curve (based on the known volumetric efficiency at P_e/P_i equal to unity) is plotted for comparison. The fact that the actual curve shows a more negative slope than the theoretical curve is probably due to the following effects:

1. At high values of P_e/P_i the time during which there is a pressure drop across the inlet port favorable for inflow is decreased.

2. During the time when there is a favorable pressure drop across the port the mean pressure drop is less at high values of P_e/P_i.

It should be stated that in this work the volumetric efficiency is based throughout on the conditions in the inlet system immediately ahead of the engine cylinder; so any estimate of the net power available must necessarily include an estimate of the power required to bring the air to the particular inlet conditions under consideration.

Brake Horsepower

The variation of brake horsepower with exhaust pressure is shown in Figure 4. There is an almost linear reduction of power with increasing exhaust pressure except at the lower pressures. Here, in the range of maximum output, the rate of change is somewhat less.

Brake Specific Air Consumption

Figure 5 shows the effect of increased exhaust pressure on the specific air consumption calculated on the brake horsepower. At an inlet pressure of 50 inches Hg. there seems to be an optimum exhaust pressure of about 40 inches Hg. for minimum air consumption. Beyond the minimum of this curve and at 30 and 40 inches Hg. inlet pressure there is a pronounced increase in specific air consumption with increasing exhaust pressure. Because the fuel air ratio was kept practically constant these curves are also indicative of the variation of specific

fuel consumption with exhaust pressure.

Mean Effective Pressures

The effect of exhaust pressure on the mean effective pressures is shown in Figure 6. The brake mean effective pressures were calculated from the known power output of the engine. The indicated mean effective pressures were obtained from two series of indicator diagrams; the first was made with the inlet pressure held constant and the second was made with the exhaust pressure held constant. Since the indicator diagrams were necessarily made with only one sparkplug in operation, quantitative values based thereon should be viewed with caution. Results based on the indicator diagrams, however, were remarkably consistent and it is probable that any error caused by single plug operation is small, as the points obtained with single plug operation shown on Figure 4 agree very closely with points obtained with dual plugs.

Both the brake m.e.p. and the indicated m.e.p. decrease with increasing exhaust pressure and the similarity of the two curves at 40 inches Hg. inlet pressure was such that the construction of parallel curves through the points of determined indicated m.e.p. at 30 and 50 inches Hg. inlet pressure appeared logical. That this assumed relationship between indicated m.e.p. and exhaust pressure is substantially correct is shown in Figure 7 where the indicated horsepower, computed from the curves of indicated m.e.p., is seen to vary directly as the air consumption.

A breakdown of the mean effective pressures at one inlet pressure is shown in Figure 8. Here it is assumed that the indicated m.e.p. is the sum of the brake m.e.p., the pumping m.e.p., and the friction

m.e.p. The indicated, brake, and friction m.e.p. decrease with increasing exhaust pressure. The pumping m.e.p. increases with increasing exhaust pressure, but since the pumping m.e.p. is a small fraction of the indicated or brake m.e.p. it is evident that the major effect in the reduction of engine output is that of the reduced volumetric efficiency at the higher exhaust pressures.

For comparative purposes a set of similar curves in which the inlet pressure is the only variable is plotted in Figure 9. This curve substantiates the well known fact that the indicated, brake, and friction m.e.p. all increase with the inlet pressure. The pumping m.e.p. is practically constant.

Indicator Diagrams

The effects of variations in exhaust pressure on the other variables already discussed may be illustrated and substantiated by means of the indicator diagrams shown in Figures 10 and 11. In these diagrams the only variable is the exhaust pressure and its effect on the maximum and mean pressures and on the pumping loops is clearly evident. In turn the volumetric efficiency can be related to the pumping loop, where it is seen that there is a variation of both the time and magnitude of the pressure drop across the inlet valve with a change in exhaust pressure.

For comparative purposes indicator diagrams in which the inlet pressure is the only variable are included in Figures 12 and 13. The relation of the pumping loops to the volumetric efficiency as the inlet and exhaust pressures are varied is shown in Figure 14. While the shape of the pumping loop varies with the inlet pressure at a given exhaust pressure, the pumping m.e.p. remains practically constant. On

the other hand, when the exhaust pressure is varied at a given inlet pressure, there is an appreciable increase in pumping m.e.p. with an increase of exhaust pressure.

Temperature of Exhaust Gases

In the conduct of this investigation particular emphasis was placed on the proper measurement of the exhaust gas temperatures, but the results obtained were somewhat disappointing. Figure 15 is a plot of these temperatures against exhaust pressure. T_4 is the temperature in the exhaust manifold adjacent to the cylinder. T_3 is the temperature of the thermocouple in the calorimeter closest to the cylinder and invariably this was the highest indicating thermocouple of the three in the calorimeter. It was hoped that there would be no appreciable temperature drop within the calorimeter, but this was not the case. There was a marked spread of the temperatures as measured by all thermocouples but there was a consistent decrease in the temperature with increase in distance from the cylinder. The temperature spread was much greater at high exhaust pressures than at low pressures. Since the high exhaust pressures were accompanied by relatively low rates of airflow, this temperature spread is probably due to the fact that the velocity of the gases in the calorimeter is lower at high pressures.

There seemed to be no correlation of the temperature in the manifold (T_4) with inlet pressure. There was an almost linear increase in this temperature with increase in exhaust pressure. Conversely the temperatures in the calorimeter showed an almost linear decrease in temperature with increasing exhaust pressure. This is not understood, but it is believed to be representative of the conditions that would exist in any CET system* where the engine exhaust gases alone were

*Compressor, engine, turbine combination

adequately mixed and led to a turbine.

<u>Application to a Compressor-Engine-Turbine System</u>

The effect of raised exhaust pressures on the engine output, and particularly the reduced volumetric efficiency which accompanies raised exhaust pressures, would seem to preclude the possibility of obtaining any substantial increase in power in a CET system utilizing this principle. A careful study, however, indicates that the curve of net total power vs. exhaust pressure reaches a maximum at a relatively high exhaust pressure. The results of this study are shown graphically in Figures 16 and 17, and in tabular form in Table I.

This work is based on the following assumptions:

1. System is operating in a standard atmosphere (N.A.C.A. Report #218)

2. Airplane speed is 300 m.p.h. indicated airspeed, full effect of ram on pressure and temperature utilized.

3. The turbine, engine, and compressor are directly connected to the propeller shaft.

4. Turbine and compressor efficiencies are 0.70.

5. The compressor works on the mixture of vaporized fuel and air.

6. The highest measured temperature in the calorimeter plus a correction for inlet temperature is the temperature of the gases to the turbine and the turbine is capable of operating at these temperatures.

7. The net total power of the CET system is equal to the measured engine brake horsepower minus the computed compressor power plus the computed turbine power.

8. Compressor and turbine work are as computed by means of "A Table of Thermodynamic Properties of Air", Keenan and Kaye, M.I.T., Cambridge, Massachusetts.

As shown in Figure 16, in each case the maximum power is available at an exhaust pressure slightly less than the inlet pressure but substantially greater than atmospheric pressure. There is a tendency for the peaks of these curves to shift to lower exhaust pressures with increasing altitudes, but the optimum exhaust pressure/atmospheric pressure ratio seems to increase with altitude. This indicates that up to fairly high exhaust pressures the reduction in engine power because of lowered volumetric efficiency and high back pressure is more than offset by the increase in turbine power resulting from the increase in pressure drop through the turbine.

Figure 17 represents an attempt to correlate the computed results by means of a nondimensional plot of the ratio of the horsepower available to the horsepower available at P_e/P_i equal to unity against the ratio P_e/P_i. The resulting curves are somewhat disappointing, but they are included as being of interest because they do indicate that in each case maximum power is available at some value of P_e/P_i between 0.8 and 1.0.

In Table I the work per pound of air is tabulated for each of the components of the system. A study of this table shows the great increase in the percentage of net total work done by the turbine as the exhaust pressure and/or altitude is increased. This large percentage of total work done by the turbine is not representative of the percentage of turbine work which would be expected in a multi-cylinder aircraft powerplant. In the single cylinder test setup the friction horsepower is much higher than the friction horsepower per

cylinder which would be expected in the multi-cylinder installation. Consequently, the multi-cylinder installation should give higher peak powers but they should occur at the optimum exhaust pressures indicated in Figures 16 and 17.

CONCLUSIONS

The study of exhaust back pressure on power plant performance leads to certain well defined conclusions that may be stated as follows:

1. Mass Rate of Air Flow falls off linearly with increase in exhaust back pressure.

2. Volumetric Efficiency falls off linearly with increase in exhaust back pressure, but the decrease is less with high values of manifold pressure.

3. Volumetric Efficiency is a linear function of P_e/P_i and it decreases as this pressure ratio increases.

4. Brake Horsepower decreases with increasing back pressure, but at low values of back pressure the change is not exactly linear.

5. Brake Specific Air Consumption generally increases with increase in exhaust back pressure and the increase is greatest at the lower values of manifold pressure.

6. i.m.e.p., b.m.e.p., and f.m.e.p. decrease with increase in exhaust pressure, but p.m.e.p. increases as the back pressure is increased.

7. The temperature in the exhaust manifold increases with increase in exhaust back pressure, but does so independently of inlet manifold pressure. As distance from the cylinder is increased, however, the temperature drops with increase in back pressure and the effect is most pronounced with lower values of inlet manifold pressure.

8. The maximum net power output in a CET system is obtained at a back pressure substantially higher than atmospheric and the value of the pressure ratio (P_e/P_i) for which it is obtained varies from 0.8 to 1.0.

INDEX OF CURVES AND TABLES

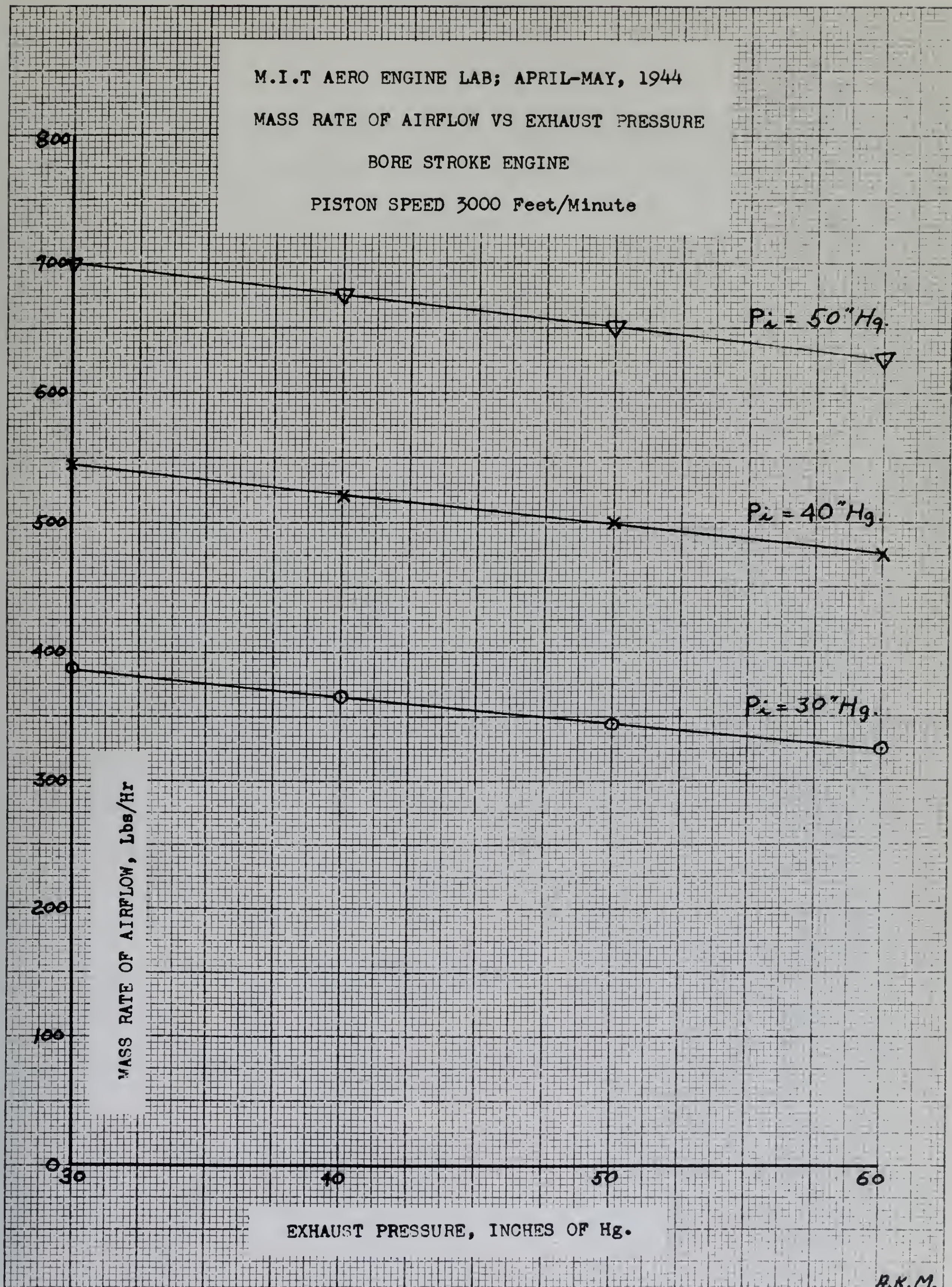
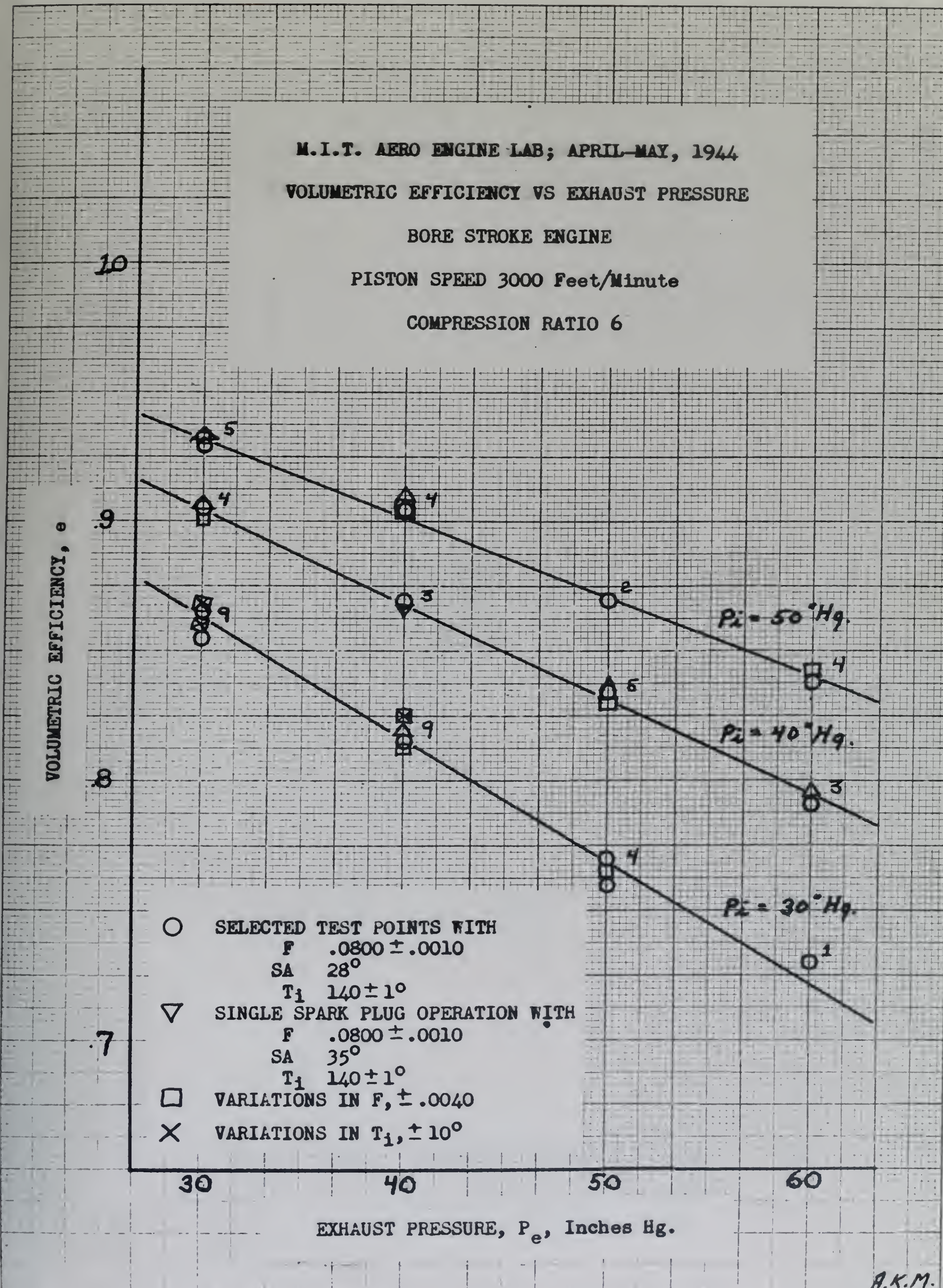
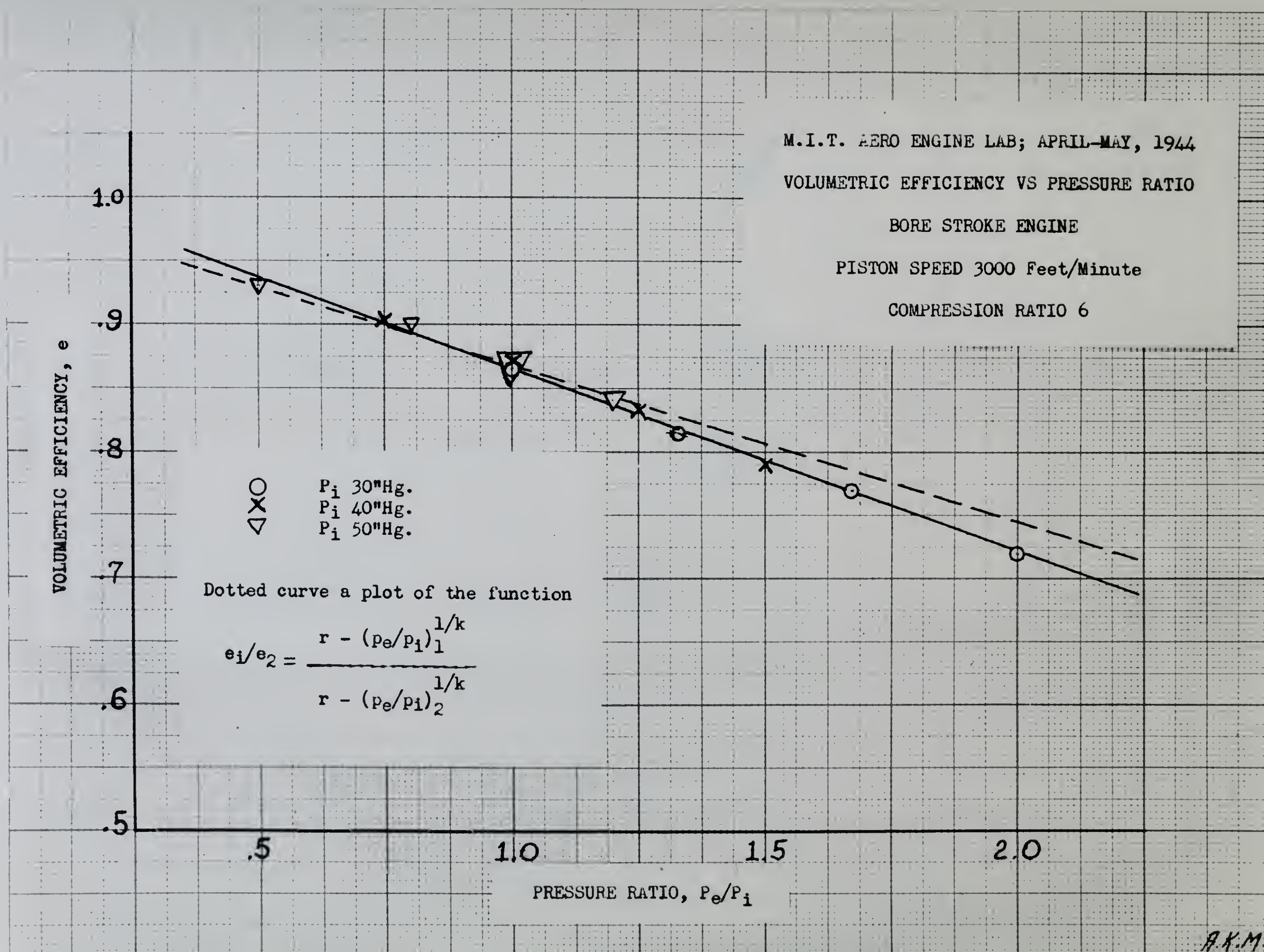

M.I.T AERO ENGINE LAB; APRIL-MAY, 1944
MASS RATE OF AIRFLOW VS EXHAUST PRESSURE
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
800
700
600
500
400
300
200
100
0
30
40
50
60
Pi = 50"Hg.
Pi = 40"Hg.
Pi = 30"Hg.
MASS RATE OF AIRFLOW, Lbs/Hr
EXHAUST PRESSURE, INCHES OF Hg.
R.K.M.

Fig. 1



M.I.T. AERO ENGINE LAB; APRIL–MAY, 1944
VOLUMETRIC EFFICIENCY VS EXHAUST PRESSURE
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
COMPRESSION RATIO 6
VOLUMETRIC EFFICIENCY, e
1.0
.9
.8
.7
P_i = 50" Hg.
P_i = 40" Hg.
P_i = 30" Hg.
SELECTED TEST POINTS WITH
F .0800 ± .0010
SA 28°
T_i 140 ± 1°
SINGLE SPARK PLUG OPERATION WITH
F .0800 ± .0010
SA 35°
T_i 140 ± 1°
VARIATIONS IN F, ± .0040
VARIATIONS IN T_i, ± 10°
30
40
50
60
EXHAUST PRESSURE, P_e, Inches Hg.
A.K.M.

Fig. 2



M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
VOLUMETRIC EFFICIENCY VS PRESSURE RATIO
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
COMPRESSION RATIO 6
P_i 30"Hg.
P_i 40"Hg.
P_i 50"Hg.
Dotted curve a plot of the function
$e_1/e_2 = \frac{r - (p_e/p_i)_1^{1/k}}{r - (p_e/p_i)_2^{1/k}}$
VOLUMETRIC EFFICIENCY, e
PRESSURE RATIO, P_e/P_i
1.0
.9
.8
.7
.6
.5
.5
1.0
1.5
2.0
A.K.M.

Fig. 3

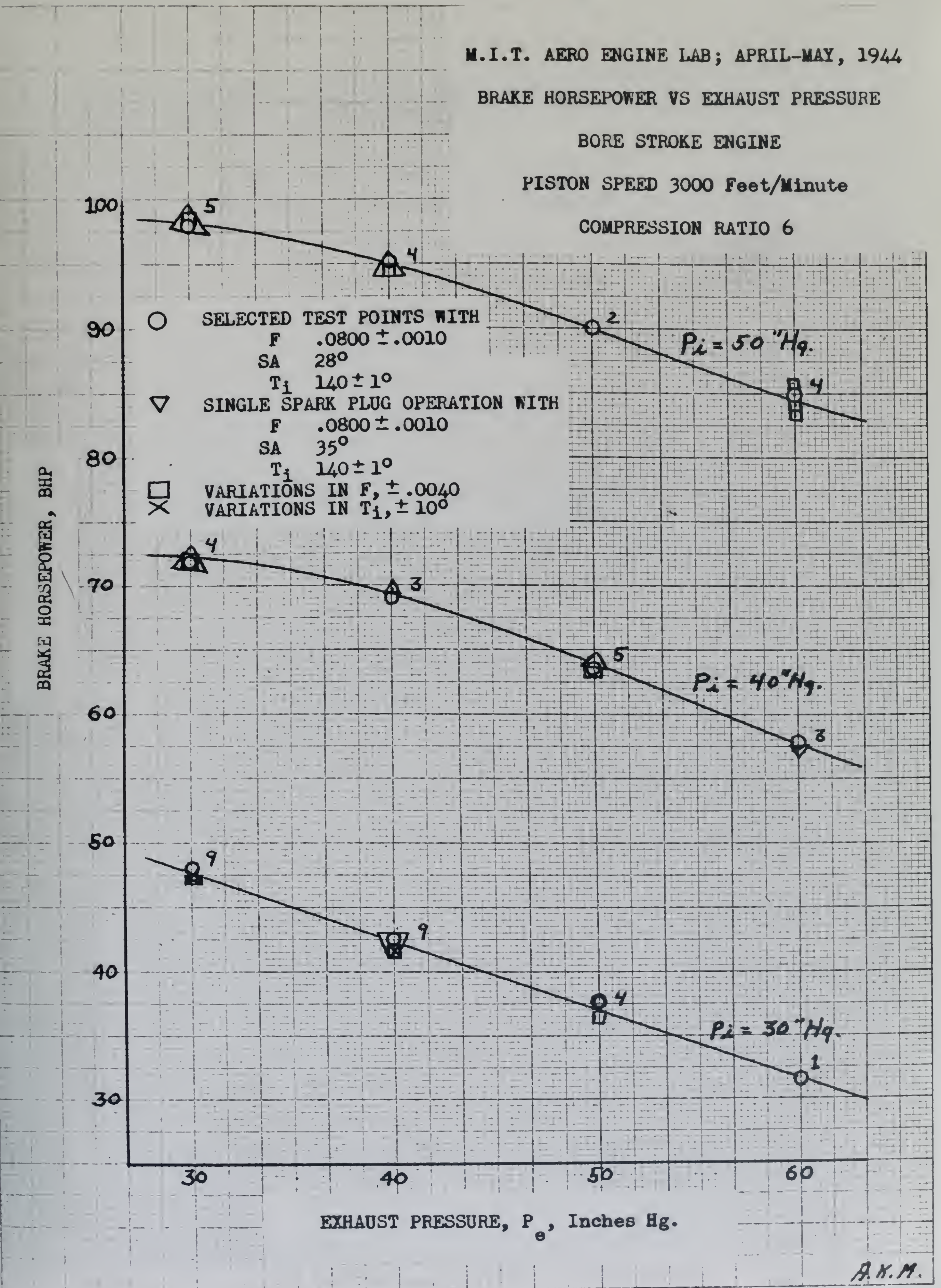

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
BRAKE HORSEPOWER VS EXHAUST PRESSURE
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
COMPRESSION RATIO 6
○ SELECTED TEST POINTS WITH
F .0800 ± .0010
SA 28°
T_i 140 ± 1°
▽ SINGLE SPARK PLUG OPERATION WITH
F .0800 ± .0010
SA 35°
T_i 140 ± 1°
□ VARIATIONS IN F, ± .0040
X VARIATIONS IN T_i, ± 10°
P_i = 50 "Hg.
P_i = 40"Hg.
P_i = 30"Hg.
BRAKE HORSEPOWER, BHP
EXHAUST PRESSURE, P_e, Inches Hg.
100
90
80
70
60
50
40
30
30
40
50
60
A.K.M.

Fig. 4

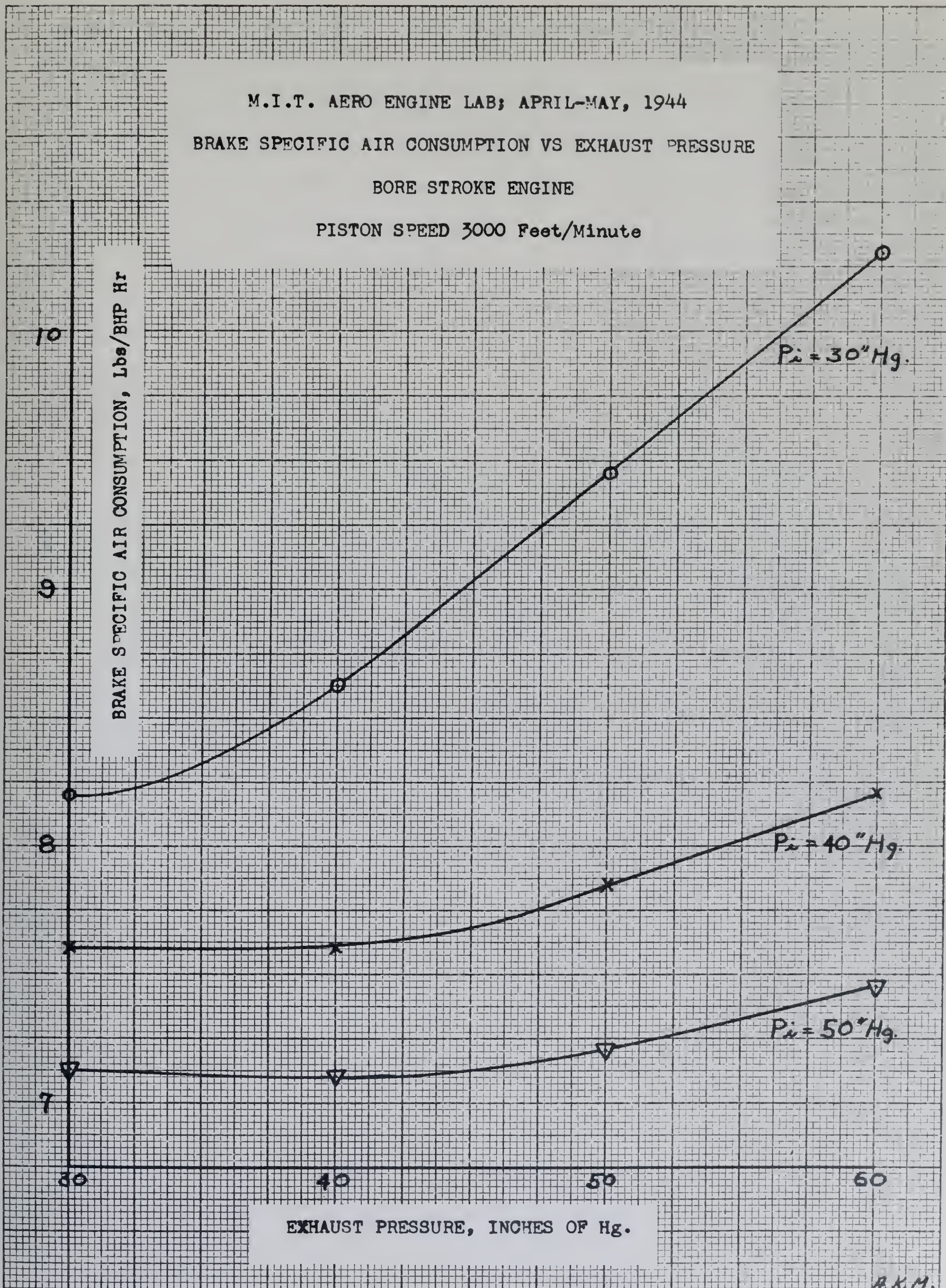
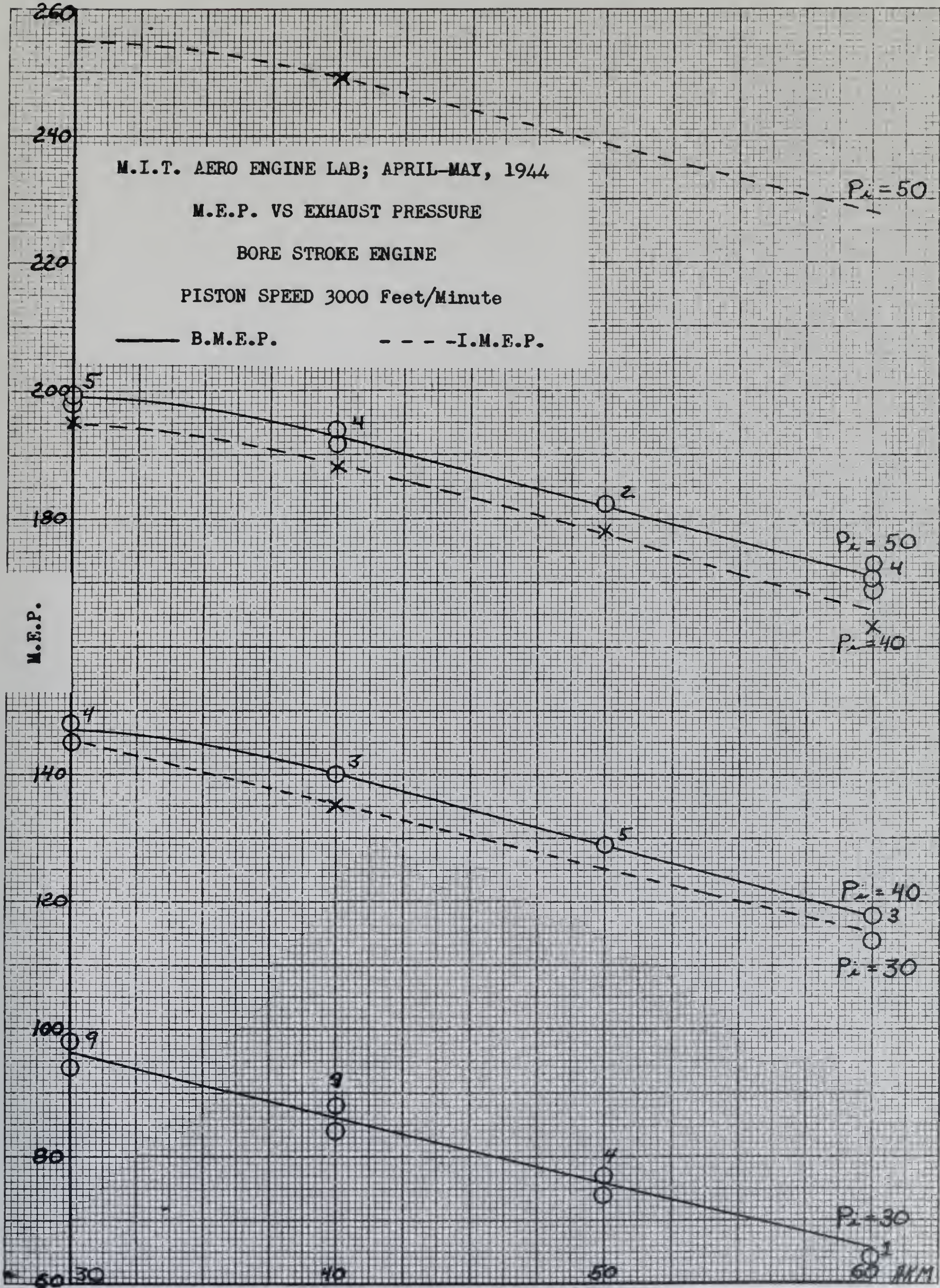

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
BRAKE SPECIFIC AIR CONSUMPTION VS EXHAUST PRESSURE
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
BRAKE SPECIFIC AIR CONSUMPTION, Lbs/BHP Hr
10
9
8
7
Pi = 30"Hg.
Pi = 40"Hg.
Pi = 50"Hg.
30
40
50
60
EXHAUST PRESSURE, INCHES OF Hg.
A.K.M.

Fig. 5



EXHAUST PRESSURE, INCHES OF Hg.

Fig. 6

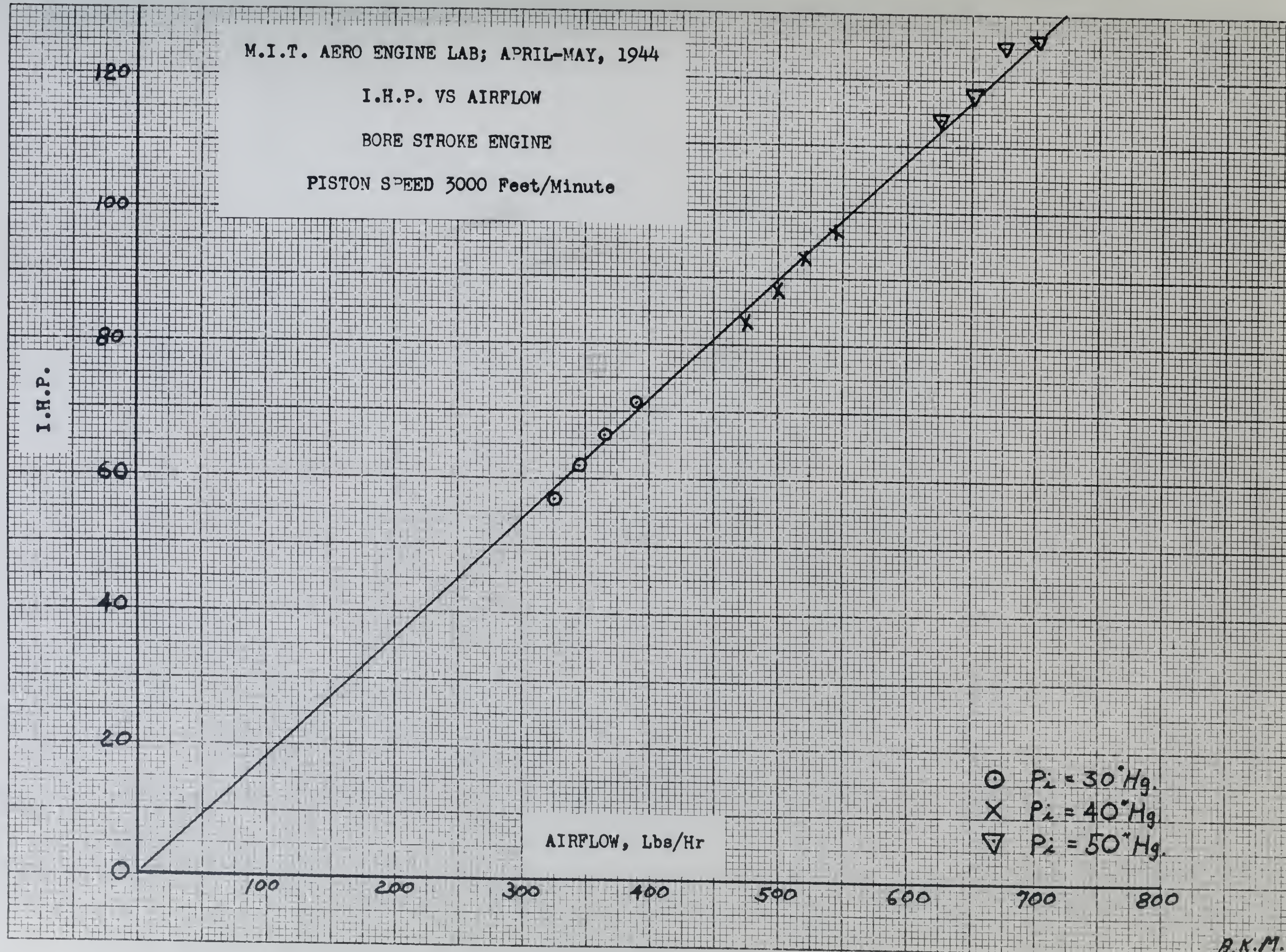

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
I.H.P. VS AIRFLOW
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
I.H.P.
AIRFLOW, Lbs/Hr
0
20
40
60
80
100
120
100
200
300
400
500
600
700
800
Pi = 30" Hg.
Pi = 40" Hg.
Pi = 50" Hg.
R.K.M.

Fig. 7

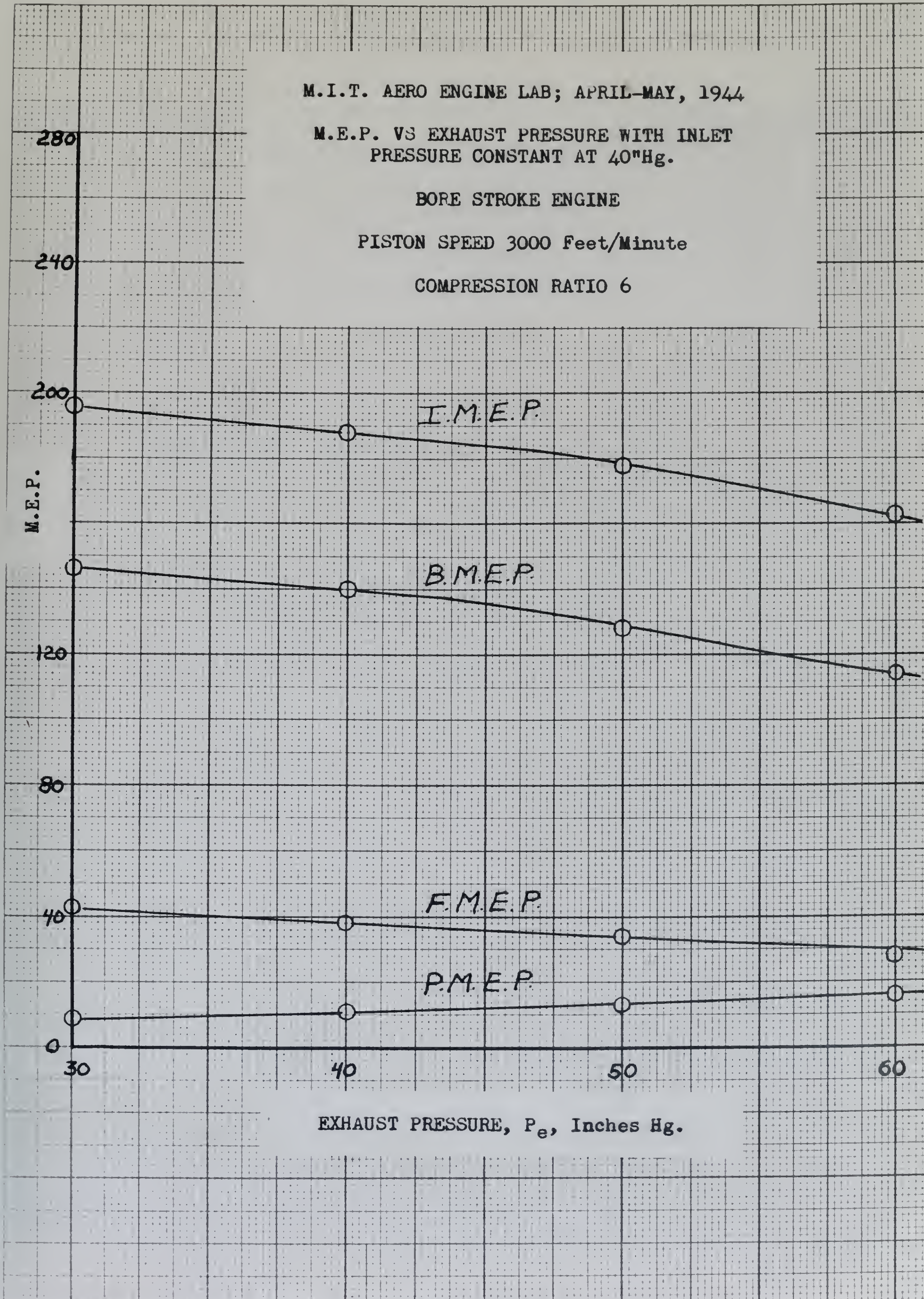

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
M.E.P. VS EXHAUST PRESSURE WITH INLET PRESSURE CONSTANT AT 40"Hg.
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
COMPRESSION RATIO 6
280
240
200
120
80
40
0
M.E.P.
I.M.E.P.
B.M.E.P.
F.M.E.P.
P.M.E.P.
30
40
50
60
EXHAUST PRESSURE, P_e, Inches Hg.

Fig. 8

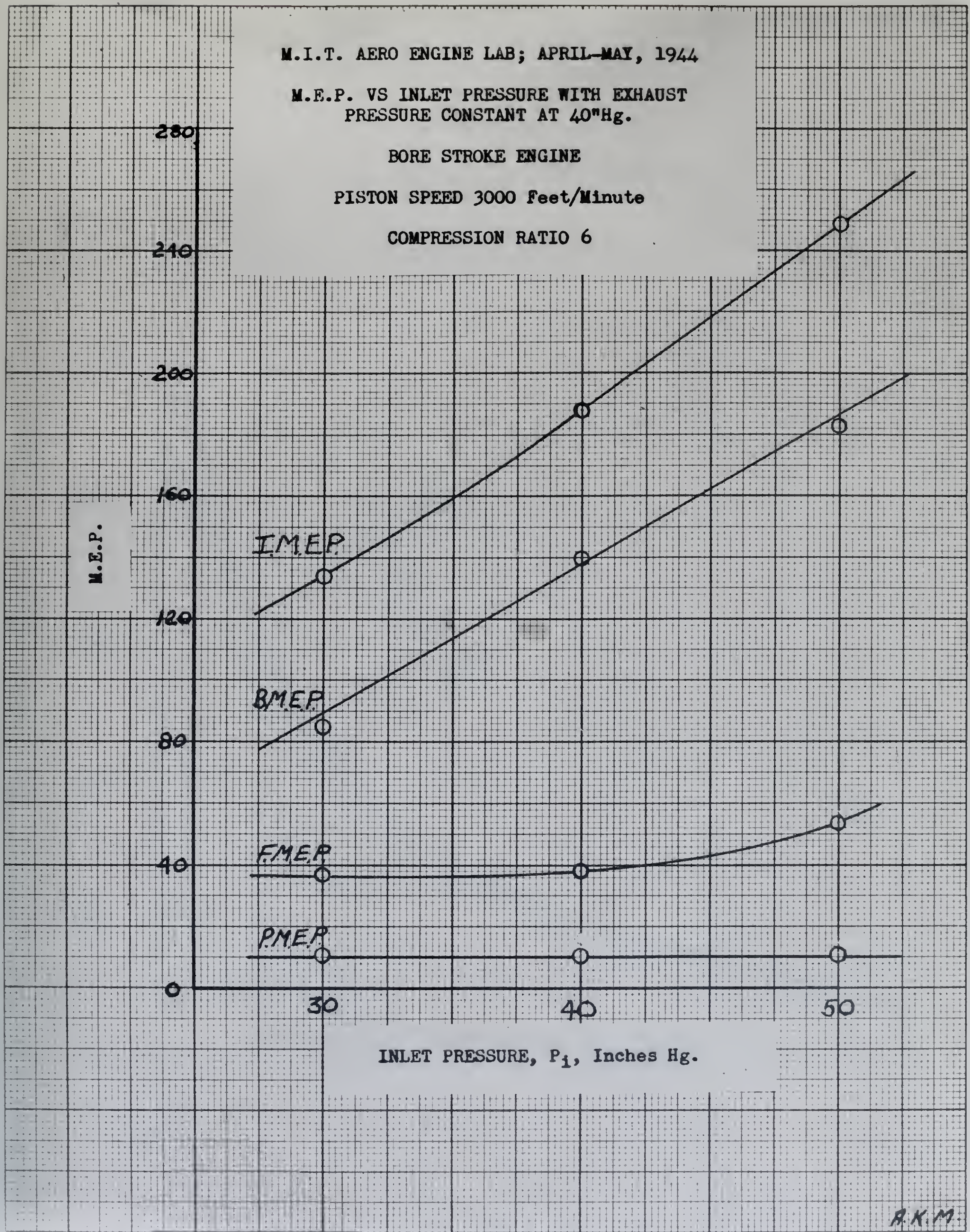

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
M.E.P. VS INLET PRESSURE WITH EXHAUST PRESSURE CONSTANT AT 40"Hg.
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
COMPRESSION RATIO 6
280
240
200
160
120
80
40
0
M.E.P.
I.M.E.P.
B.M.E.P.
F.M.E.P.
P.M.E.P.
30
40
50
INLET PRESSURE, P_i, Inches Hg.
A.K.M.

Fig. 9

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944

EFFECT OF EXHAUST PRESSURE ON THE INDICATOR CARD WITHOUT PUMPING LOOP WITH INLET PRESSURE CONSTANT AT 40"Hg

BORE STROKE ENGINE

PISTON SPEED 3000 Feet/Minute

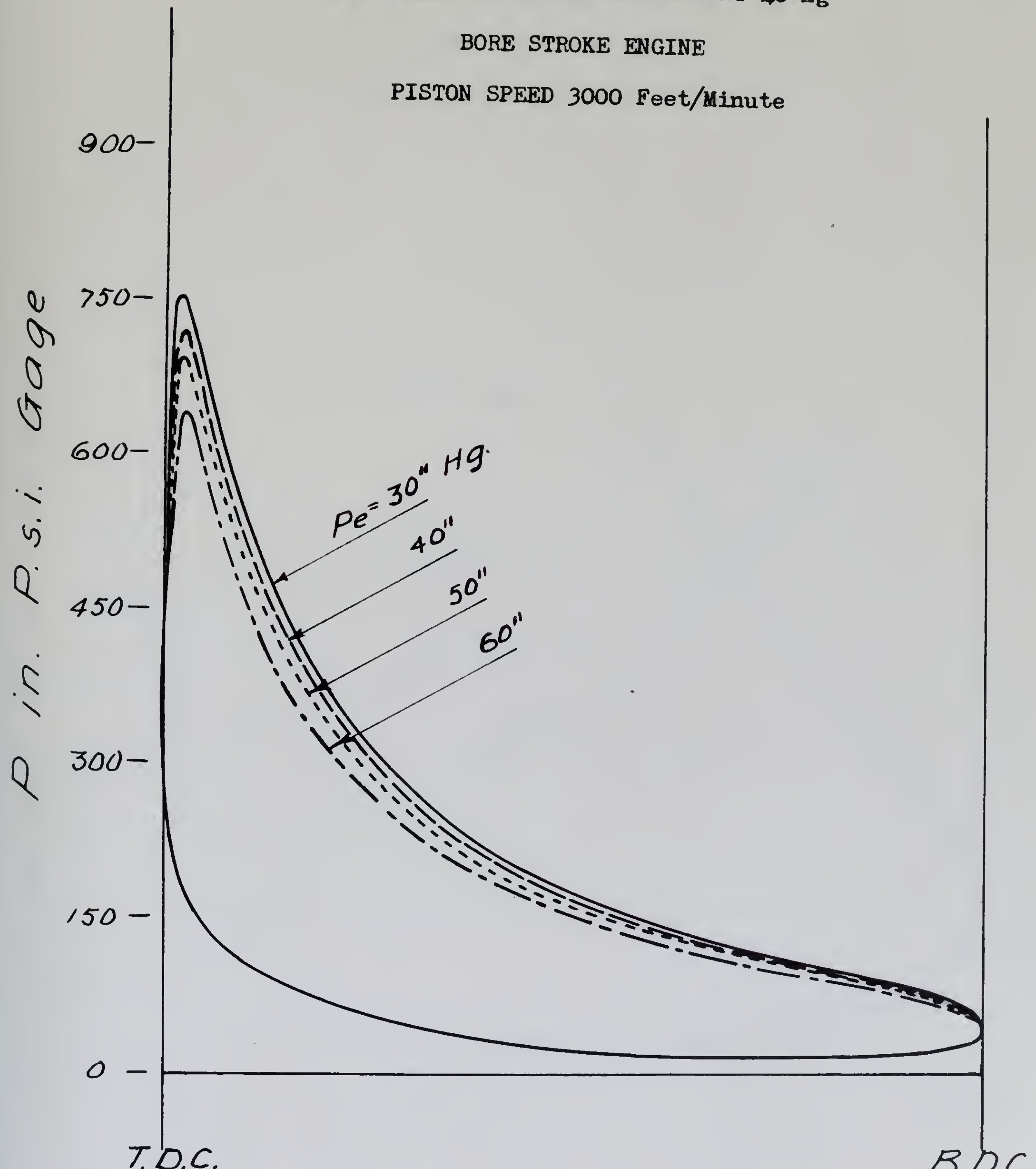


Fig. 10

M.I.T. AERO ENGINE LAB; APRIL–MAY, 1944

EFFECT OF EXHAUST PRESSURE ON THE PUMPING DIAGRAM WITH INLET PRESSURE CONSTANT AT 40 INCHES OF Hg

BORE STROKE ENGINE

PISTON SPEED 3000 Feet/Minute

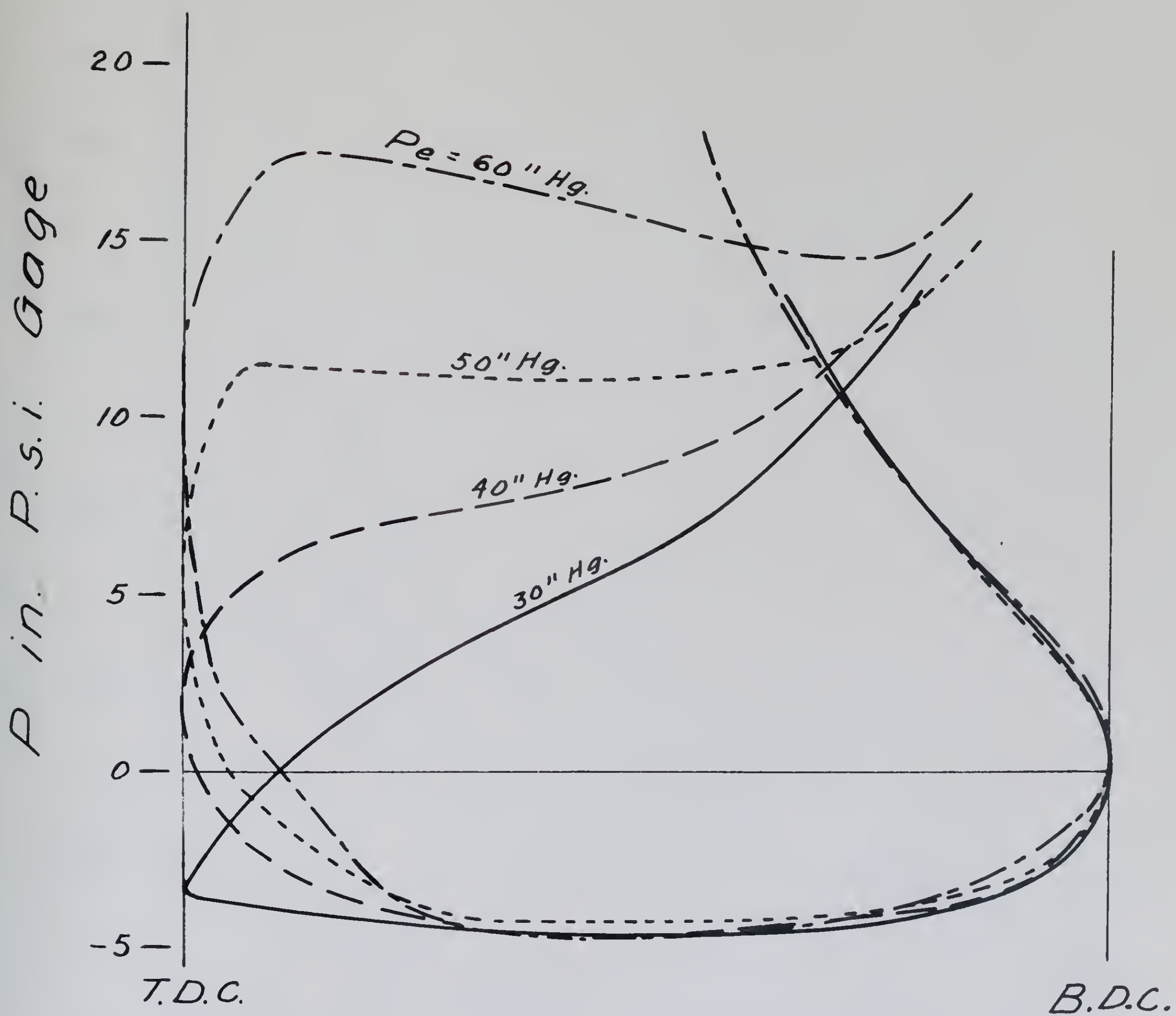


Fig. 11

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944

EFFECT OF INLET PRESSURE ON THE
INDICATOR CARD WITHOUT PUMPING LOOP
WITH EXHAUST PRESSURE CONSTANT AT 40"Hg

BORE STROKE ENGINE

PISTON SPEED 3000 Feet/Minute

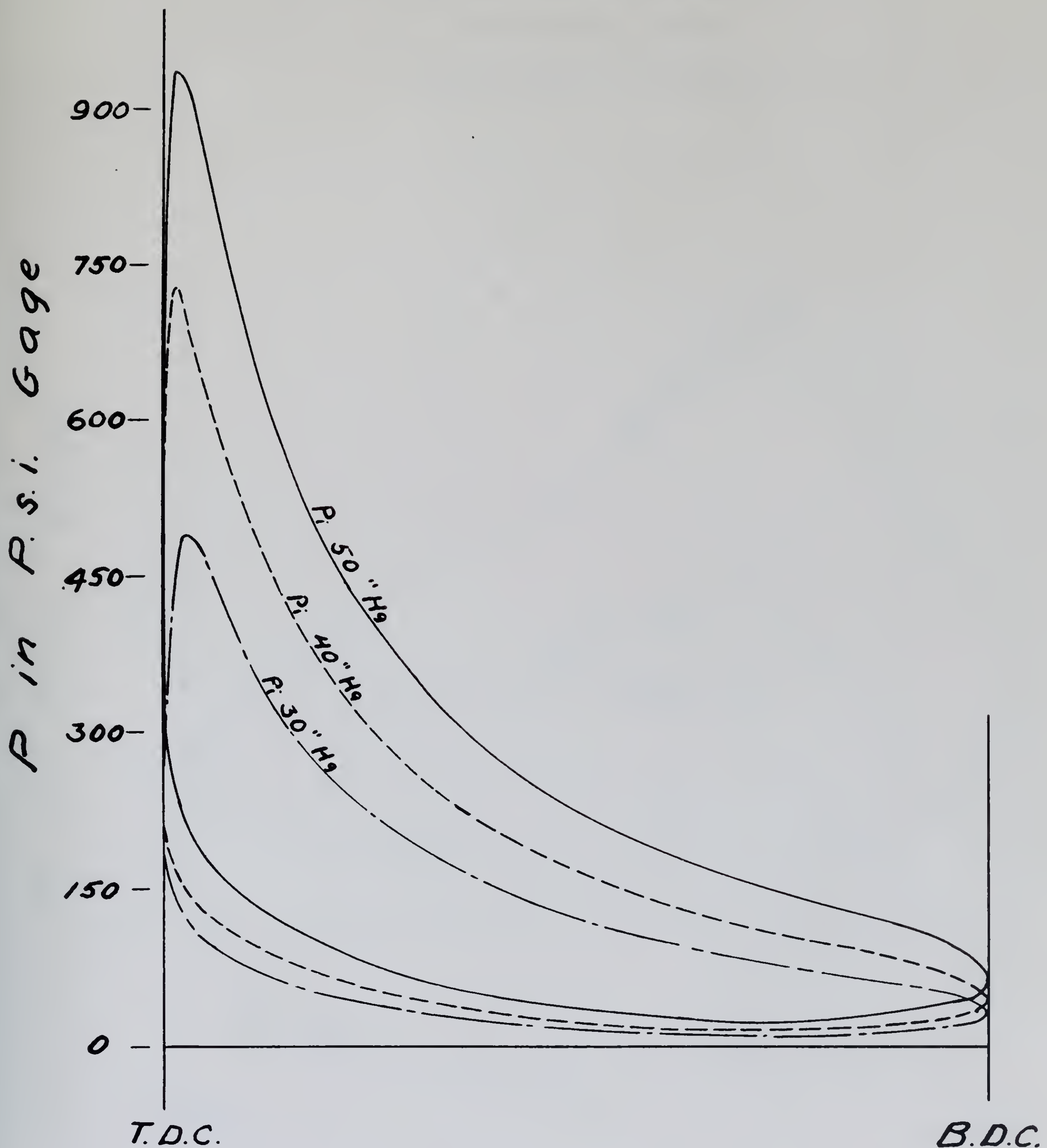


Fig. 12

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944

EFFECT OF INLET PRESSURE ON THE
PUMPING DIAGRAM WITH EXHAUST PRESSURE
CONSTANT AT 40 INCHES OF Hg

BORE STROKE ENGINE

PISTON SPEED 3000 Feet/Minute

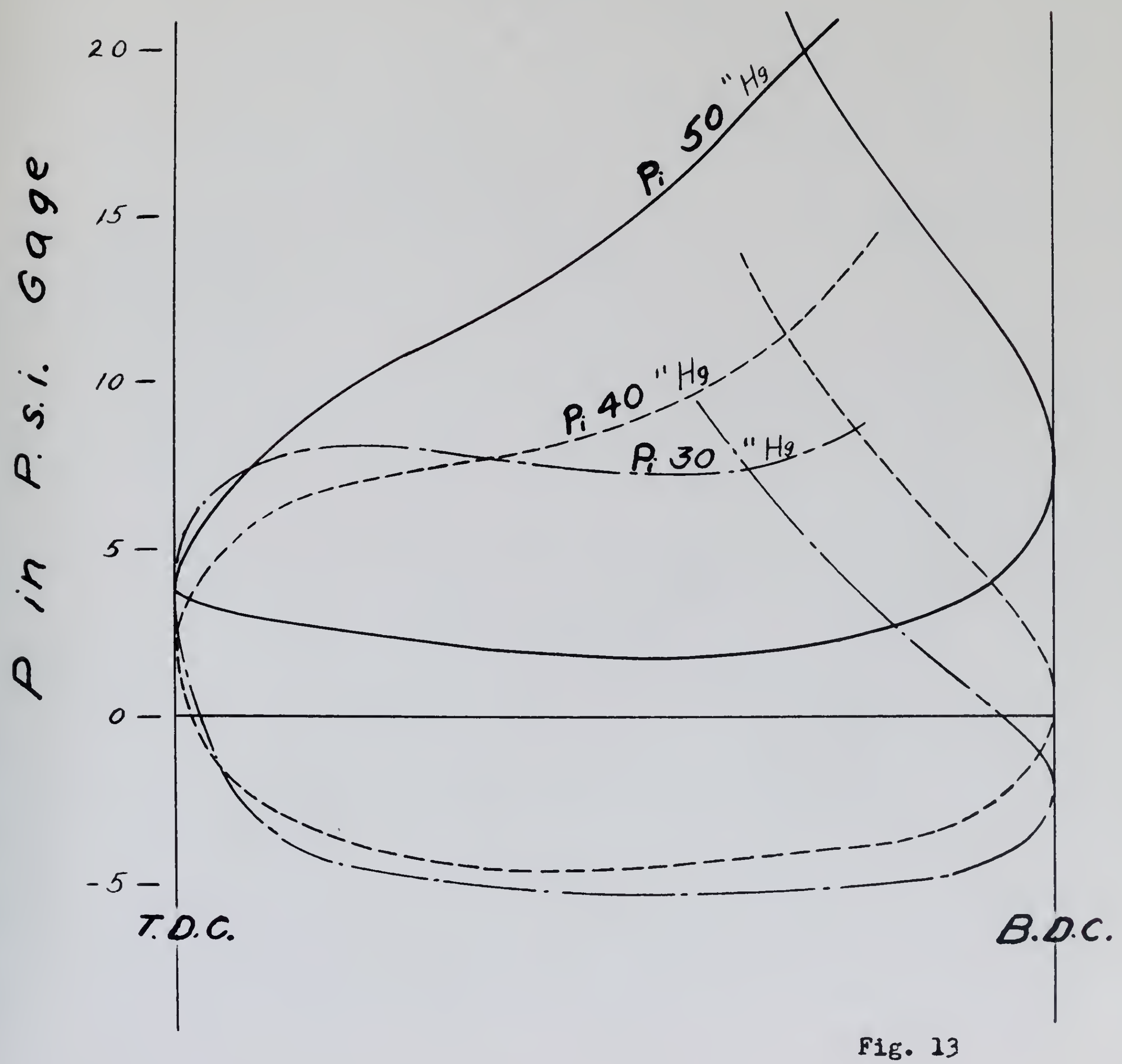
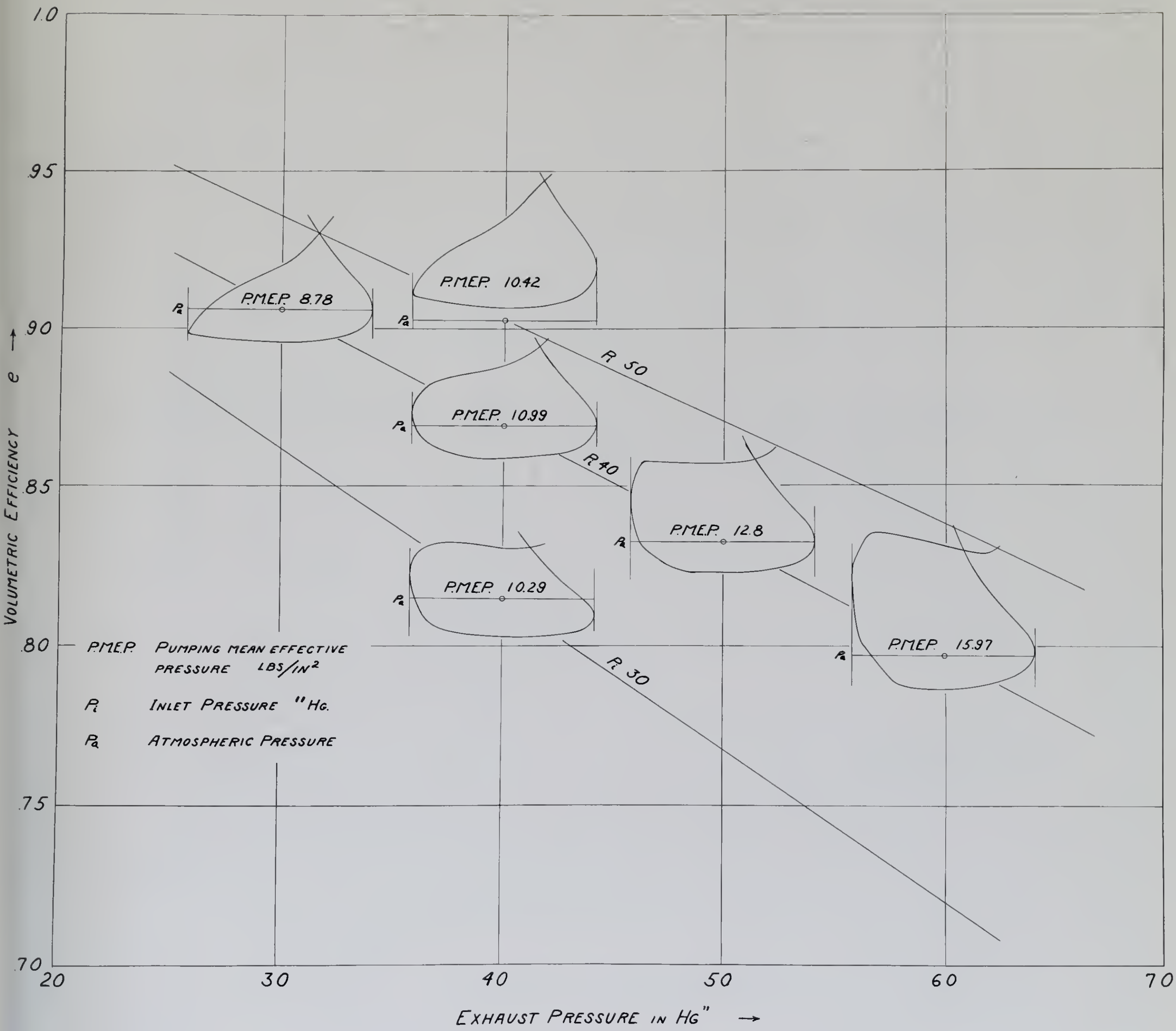


Fig. 13



B.S.R. ENGINE, PISTON SPEED 3000 FT/MIN.

RELATION OF PUMPING CYCLE TO VOLUMETRIC EFFICIENCY

FIG. 14

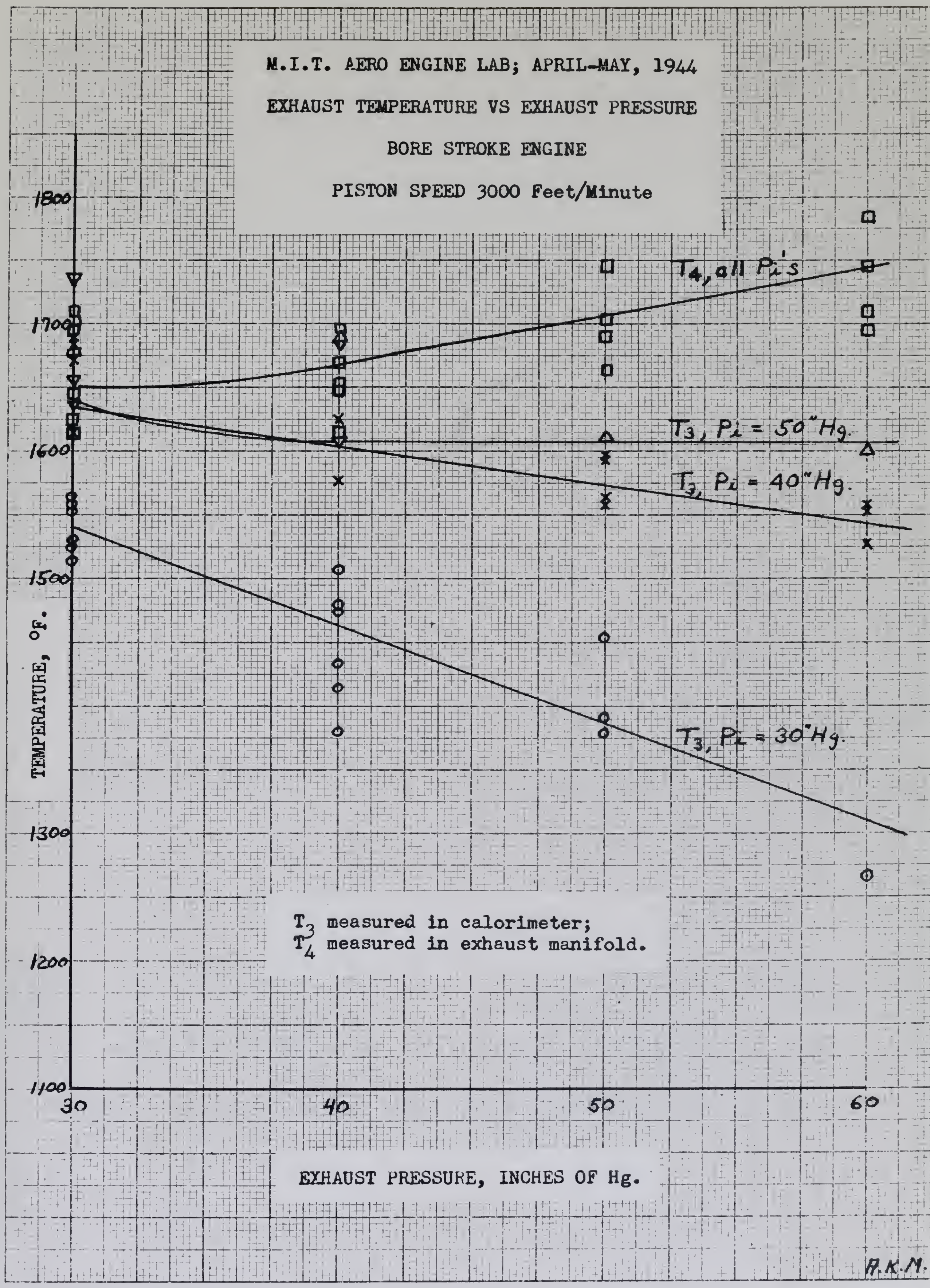
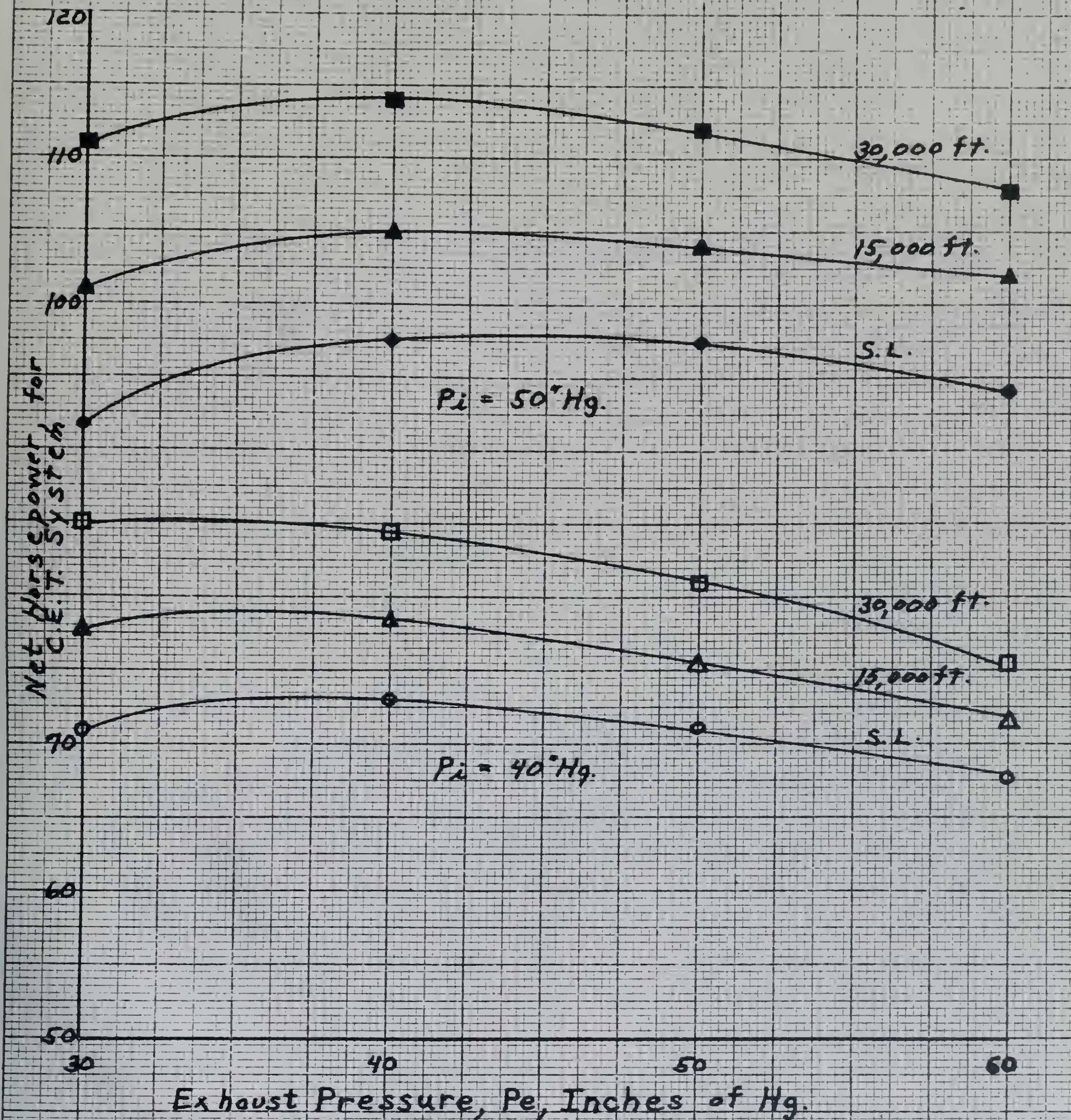

M.I.T. AERO ENGINE LAB; APRIL-MAY, 1944
EXHAUST TEMPERATURE VS EXHAUST PRESSURE
BORE STROKE ENGINE
PISTON SPEED 3000 Feet/Minute
1800
1700
1600
1500
1300
1200
1100
TEMPERATURE, °F.
T_4, all P_i's
T_3, P_i = 50" Hg.
T_3, P_i = 40" Hg.
T_3, P_i = 30" Hg.
T_3 measured in calorimeter;
T_4 measured in exhaust manifold.
30
40
50
60
EXHAUST PRESSURE, INCHES OF Hg.
A.K.M.

Fig. 15

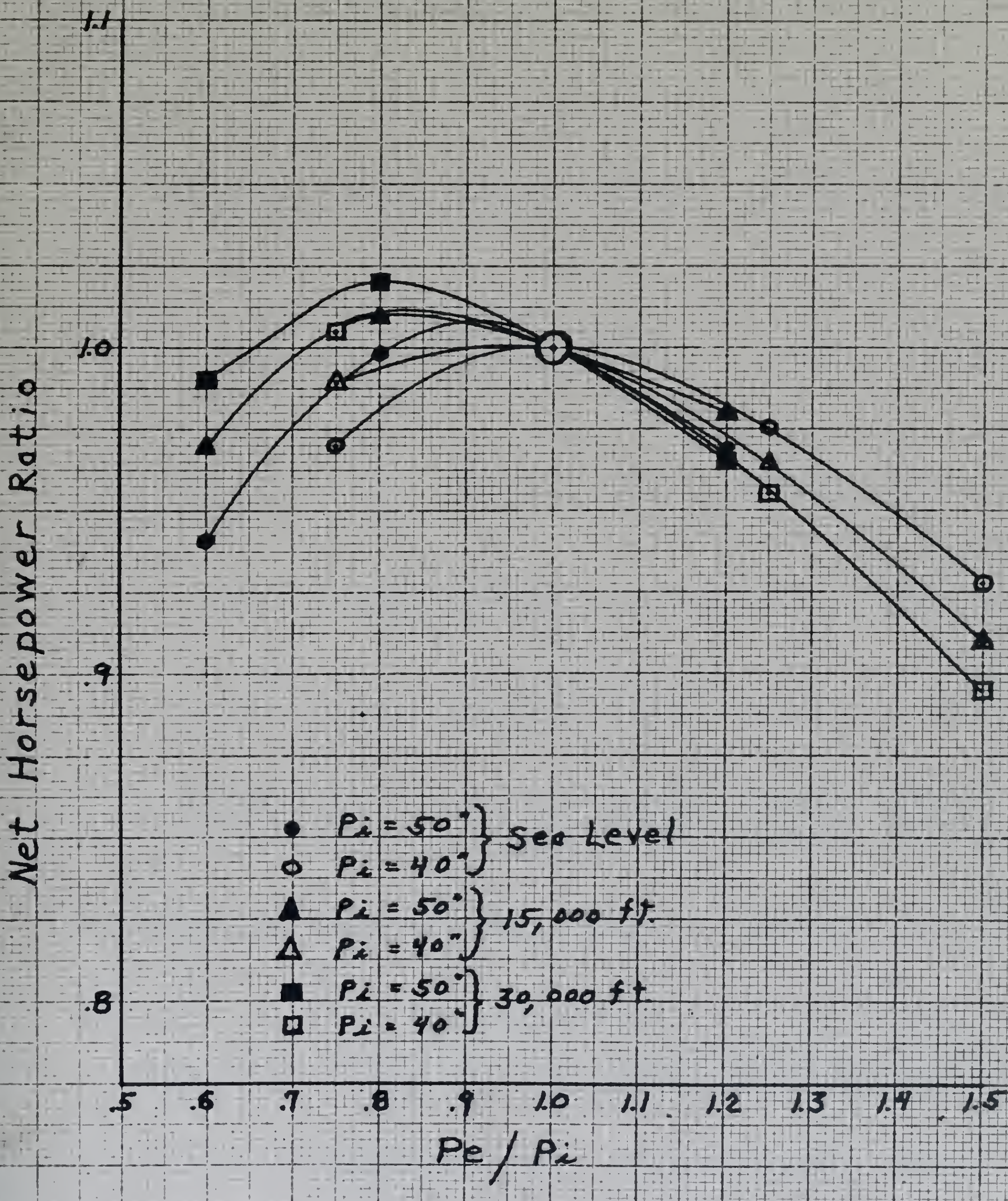


Net Horsepower vs Exhaust Pressure
for A C.E.T. System

Fig. 16.

M.I.T. - May 1944

A.K.M.



Net Horsepower Ratio vs. Pe/Pi for a C.E.T. System

Fig. 17

APPENDIX A

M.I.T. AERO ENGINE LABORATORY

SUMMARY OF RECORD RUNS WITH F = .0800 ± .0010

ENGINE B.S.R. BORE 5.25" STROKE 6.25" COMPRESSION RATIO 6

Piston Speed = 3000 ft/min ; RPM = 2884

1944

REMARKS	DATE	TIME	RUN	Bar. Cor. "Hg	"Hg BL.	PSI BMEP.	BHP.	amps. I_{ex}	ROTO-METER READING	lbs fuel W_F	"Hg P_1	"Alcohol H	°F T	lbs Air W_A	F	Degrees S.A.	"Hg h_i	"Hg h_e	°F T_x	e	T_1	T_2	T_3	T_4	psi P_{oil}	°F T_{oil}	°F T_{cyl}	psi P_{cyl}
P_m=30, P_e=30	4/13	1543	5	29.66	14.6	95.2	47	.13	17.0	30.75	1.21	14.55	80	385	.0799	28	.34	.34	147	.867	33.0	33.8	34.3	8.25	70	170	183	
																					1459	1494	1515	1625				
P_m=30, P_e=30	4/18	1303	7	30.04	15.05	97.79	48.3	.15	17.2	31.0	.82	14.8	79	388	.0799	28	-.04	-.04	140	.865	34.1	34.8	35.3	8.5		150	180	
																					1506	1538	1560	1663				
P_m=30, P_e=40	4/18	1323	10	30.04	13.25	86.04	42.5	.15	15.45	29.1	.86	13.25	80	366	.0795	28	-.03	9.96	140	.815	32.6	33.6	34.2	8.67	64	150	180	56
																					1441	1486	1507	1690				
P_m=30, P_e=50	4/18	1350	12	30.04	11.28	73.23	36.2	.12	13.9	27.2	.65	11.5	80	341	.0798	28	-.04	19.96	140	.759	30.6	32.0	32.9	9.05	64	155	180	56
																					1355	1415	1455	1748				
P_m=30, P_e=30	4/22	1050	1	30.40	14.7	95.49	47.1	.15	17.1	30.8	.36	14.5	75	385	.0800	28	-.42	-.40	140	.855	33.8	34.6	35.2	8.4	56	150	180	
																					1493	1529	1554	1647				
P_m=30, P_e=40	4/22	1105	2	30.40	13.45	87.34	43.1	.14	15.75	29.35	.38	13.25	76	368	.07925	28	-.40	9.6	140	.8125	31.6	32.7	33.4	8.55	57	150	180	
																					1398	1446	1476	1670				
P_m=30, P_e=50	4/22	1125	3	30.40	11.85	76.94	38.0	.12	14.55	28.0	.26	11.85	78	346	.0810	28	-.40	19.7	140	.770	29.7	30.8	31.5	8.67	60	150	180	
																					1317	1364	1393	1690				
P_m=30, P_e=60	4/22	1200	5	30.40	9.85	64.03	31.7	.10	13.1	26.2	.20	10.4	79	324	.0808	28	-.40	30.4	140	.722	26.3	27.6	28.5	8.8	64	150	180	
																					1171	1228	1266	1710				
P_m=40, P_e=30	4/22	1315	7	30.40	22.4	145.56	71.9	.19	29.0	43.4	10.75	21.45	73	543	.0800	28	9.55	-.40	140	.905	36.7	37.4	38.1	8.62	58	150	180	
																					1623	1654	1684	1682				
P_m=40, P_e=40	4/22	1325	8	30.40	21.5	139.66	69.0	.19	27.7	41.8	10.8	19.85	73	523	.0800	28	9.6	9.6	140	.869	34.4	35.3	35.7	8.42	58	150	180	
																					1520	1564	1577	1650				
P_m=40, P_e=50	4/25	1120	3	29.71	19.85	128.95	63.7	.17	25.75	39.8	11.35	18.15	70	500	.0796	28	10.29	20.29	140	.834	34.1	34.9	35.3		56	150	180	
																					1507	1542	1559					
P_m=40, P_e=60	4/25	1135	4	29.71	18.0	116.94	57.8	.15	23.8	37.8	11.2	16.4	71	474	.0798	28	10.29	30.29	140	.791	33.5	34.3	34.6		55	150	170	
																					1480	1515	1528					
P_m=50, P_e=60	5/4	1125	2	30.47	26.35	171	84.5	.20	35.55	50.65	21.25	23.0	76	628	.0807	28	19.95	29.95	140	.8395	35.3	35.8	36.2	38.5	71	76		62
																					1559	1582	1600	1702				
P_m=50, P_e=50	5/4	1150	5	30.47	28.1	182.5	90.2	.22	37.3	52.6	21.4	25.0	76	651	.0808	28	19.95	19.95	140	.869	35.6	36.0	36.4	37.6	72	76		62
																					1572	1590	1610	1662				
P_m=50, P_e=40	5/4	1225	7	30.47	29.9	194	95.8	.22	38.45	53.9	21.6	27.0	78	679	.0795	28	19.95	9.35	140	.904	35.5	35.9	36.4	37.4	70	78		62
																					1568	1586	1610	1654				
P_m=50, P_e=30	5/4	1245	9	30.47	30.6	198.5	98	.23	40.1	55.75	21.65	28.5	78	697	.0801	28	19.95	-.05	140	.930	36.0	36.5	37.0	37.4	70	78		62
																					1590	1614	1636	1654				

SEE LOG SHEETS IN FILES FOR OTHER RUNS

OBSERVERS: ANTONIAK – KENNA – McCUTCHEON

APPENDIX B

FORMULAE

Air Meter:

$$W_A = AKY\sqrt{2g\rho\Delta P}$$

Orifice Characteristics:

Diameter = 1.35 inches

Area = 1.431 sq. in.

K = 0.617

Y = 1.0

B = 0.45

$$W_A = 3600 \times 1.431 \times 0.617 \times 1.0\sqrt{\frac{2 \times 386 \times P \times 70.7}{1728 \times T \times 53.3} \times \frac{H \times .82 \times 62.4}{1728}}$$

$$W_A = 421\sqrt{\frac{P \times H}{T}}$$

0.82 = specific gravity of alcohol

62.4 = weight of a cu. ft. of water

70.7 = conversion of "Hg. to p.s.f.

53.3 = gas constant

P = pressure in front of orifice in inches of mercury; equal to gage pressure in front of orifice plus barometer; both in inches of mercury

H = orifice pressure drop in inches of alcohol

T = temperature of air entering orifice in degrees Rankine

Brake Loading:

$$H.P. = \frac{Plan}{66,000} = \frac{2\pi NFL}{33,000}$$

N = RPM

L = 21.008 inches, brake arm

F = 10 lbs. load; equivalent to 3 "Hg. by experiment

$$\text{H.P.} = \frac{2\pi N \times 10 \times (\text{"Hg.}) \times 21.008}{33{,}000 \times 3 \times 12}$$

$$\text{H.P.} = \frac{(\text{"Hg.}) \times N}{900}$$

$$\text{b.m.e.p.} = \frac{66{,}000\ \text{H.P.}}{\ell AN} = \frac{66{,}000 \times (\text{"Hg.}) \times N}{\ell AN \times 900}$$

$$= \frac{66{,}000 \times (\text{"Hg.})}{\left(\frac{6.25}{12}\right) \times \left(\frac{\pi}{4} \times \overline{5.25}^2\right) \times 900}$$

$$\text{b.m.e.p.} = 6.495 \times (\text{"Hg.})\ \text{p.s.i.}$$

where ("Hg.) is reading of Brake Load Manometer

$$\text{BHP} = \frac{P\ell AN}{66{,}000}$$

$$= \frac{P \times \left(\frac{6.25}{12}\right) \times \left(\frac{\pi}{4} \times \overline{5.25}^2\right) \times 2884}{66{,}000}$$

$$\text{BHP} = 0.494 \times \text{b.m.e.p.}$$

Volumetric Efficiency:

$$e = \frac{W_A}{nV\rho_i}$$

$$= \frac{\frac{421}{60}\sqrt{\frac{P \times H}{T}}}{\frac{2884}{2} \times \left(\frac{\pi}{4} \times \frac{\overline{5.25}^2 \times 6.25}{1728}\right)\left(\frac{P_i}{T_i} \times \frac{70.7}{53.3}\right)}$$

$$e = 0.04685\ \frac{T_i}{P_i}\sqrt{\frac{P \times H}{T}}$$

W_A = Air flow in lbs./min.

n = No. suction strokes/min.

V = Displacement volume, cu. ft.

ρ_i = Inlet air density, lbs./cu. ft.

T_i = Inlet air temperature, degrees Rankine

P, H, T = Values used in computation of W_A

APPENDIX C

SAMPLE CALCULATION CET SYSTEM

Ref. (a) "A Table of Thermodynamic Properties of Air", Keenan and Kaye

Subscript 1 = before compressor or turbine

Subscript 2 = after compressor or turbine

h_a = Enthalpy of air BTU/lb. air

h_f = Enthalpy of fuel BTU/lb. fuel

h_m = Enthalpy of mixture BTU/lb. mixture

h_{ma} = Enthalpy of mixture per lb. of air

h_e = Enthalpy of exhaust gases BTU/lb. gases

f = fuel-air ratio = .080

η_c = Compressor efficiency = .7

η_t = Turbine efficiency = .7

$$h_a + f\, h_f = h_{ma1}$$

$$h_{m1} = \frac{h_{ma1}}{1 + f} = \text{Enthalpy of mixture entering compressor}$$

Compressor Work $= \dfrac{h_{m2} - h_{m1}}{.7}$ BTU/lb. mixture

$= 1.08\, \dfrac{h_{m2} - h_{m1}}{.7}$ BTU/lb. air

where h_{m2} is obtained from Ref. (a) by means of relative pressure ratio of manifold pressure to atmospheric pressure plus ram.

Engine Work $= \dfrac{\text{BHP} \times 2545}{\text{Lbs. Air/Hr.}}$ = BTU/lb. air

$\underline{\text{Turbine Work}} = .7\ (h_{e1} - h_{e2})$ BTU/lb. ex. gases

$= 1.080 \times .7(h_{e1} - h_{e2})$ BTU/lb. air

where h_{e1} is obtained from corrected exhaust temperature and h_{e2} by relative pressure ratio of exhaust pressure to atmospheric pressure

$\underline{\text{Net System Work/Lb. Air}} = \underline{\text{Engine Work - Compressor Work + Turbine Work}}$

$$\underline{\text{Net Horsepower}} = \frac{\text{Net Work/Lb. Air} \times \text{Lbs. Air/Hour}}{2545}$$

__Example__

At: 300 m.p.h. indicated air speed

Sea Level

50" inlet pressure

50" exhaust pressure

$$P_a = 29.92 + \frac{1}{2}\,\frac{.002378}{70.7}\,(300 \times 1.47)^2 = 33.18$$

$$T_a = 519 + \frac{(300 \times 1.47)^2}{12{,}000} = 535^{\circ}\ R.$$

$$h_a = 32.41$$

$$h_f = .5T_f - 375 = .5 \times 535 - 375 = -107$$

$$h_{m1} = \frac{32.41 - .080 \times 107}{1.080} = \frac{23.85}{1.080} = 22.07$$

	$\underline{P}$	$\underline{h}$	$\underline{P_r}$	$\underline{T}$
(1)	33.18	22.07	2.064	580
(2)	50	$\underline{36.87}$	3.120	

$h_{m2} - h_{m1} = 14.8$

Compressor Work $= 1.080 \frac{14.8}{.7} = 22.8$ BTU/lb. air

Engine Work $= \frac{90.3 \times 2545}{652} = 352$ BTU/lb. air

$T_3 = 1610°$ F.

$\Delta T = -20 = 580 - (140 + 460)$

$T_e = 1590°$ F.

	T	P	h	P_r
(1)	1590	50"	424	398
(2)		29.92	355	238

$h_{e_1} - h_{e_2} = 69$

Turbine Work $= 1.080 \times .7 \times 69 = 52$ BTU/lb. air

Net Work $= 352 - 22.8 + 52 = 381$ BTU/lb. air

Net Power CET System $= \frac{381 \times 652}{2545} = 97.5$ H.P.

APPENDIX D

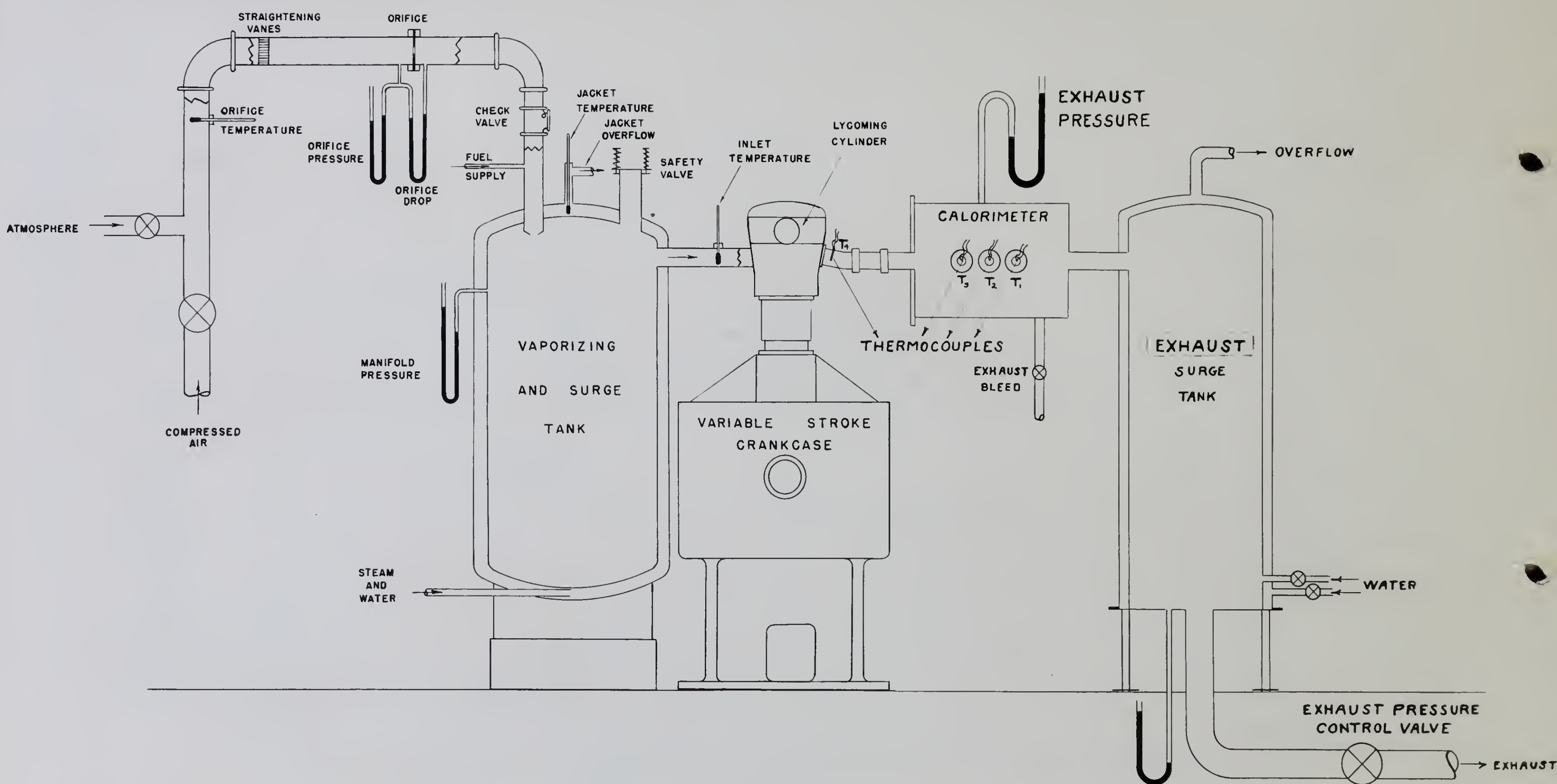


FIG. A

DIAGRAMATIC SKETCH OF ENGINE SET-UP

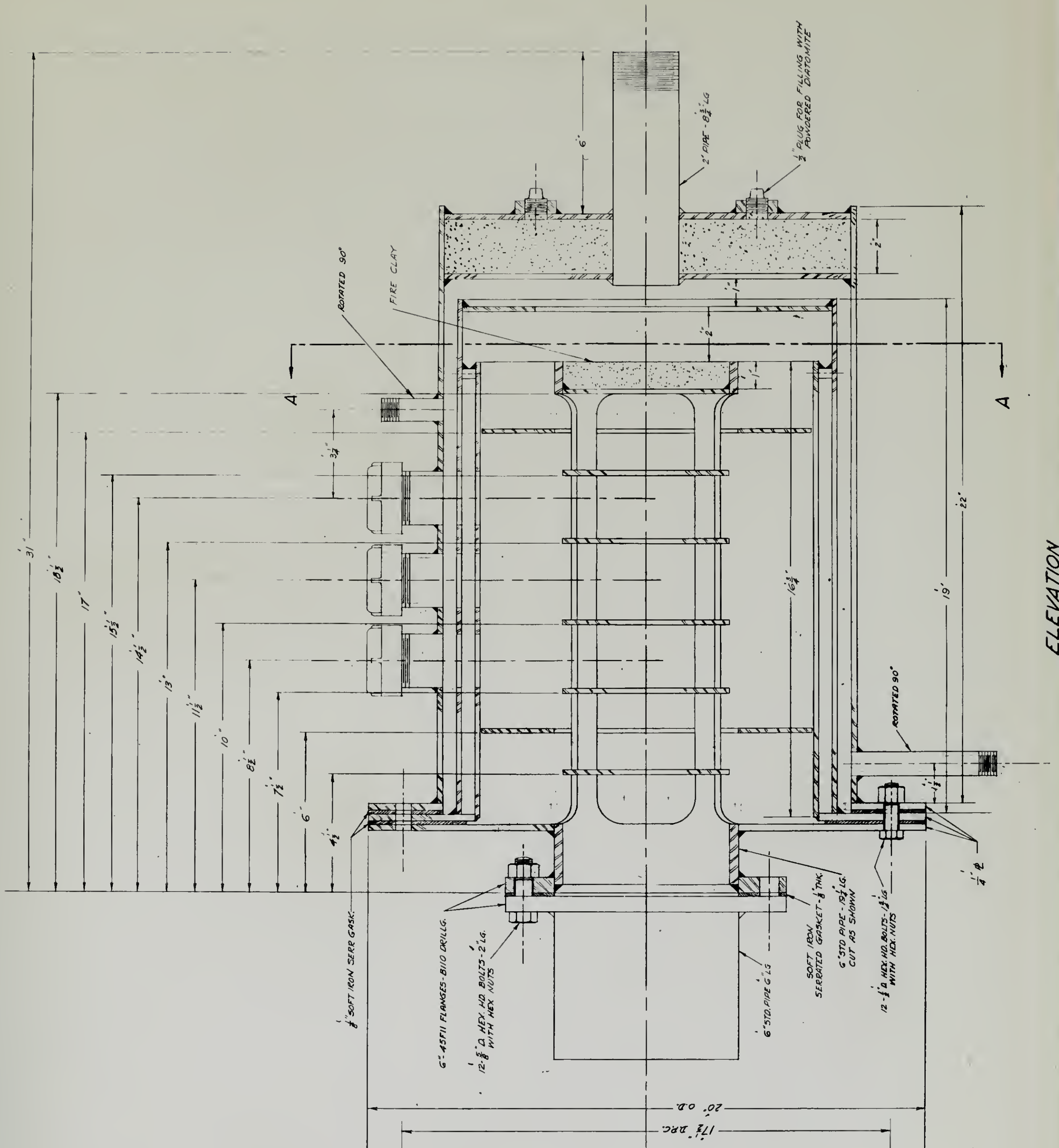


FIG. B CALORIMETER

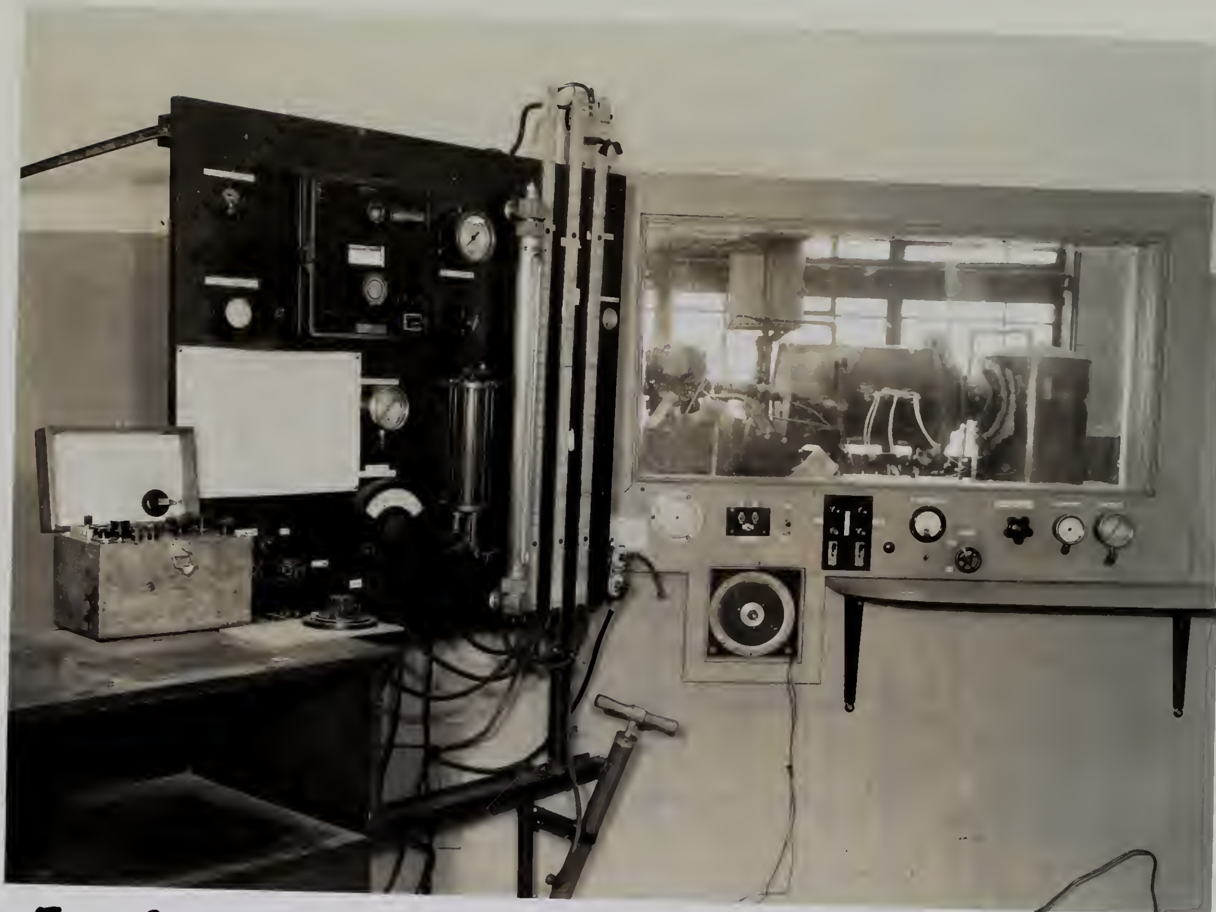


FIG. C.

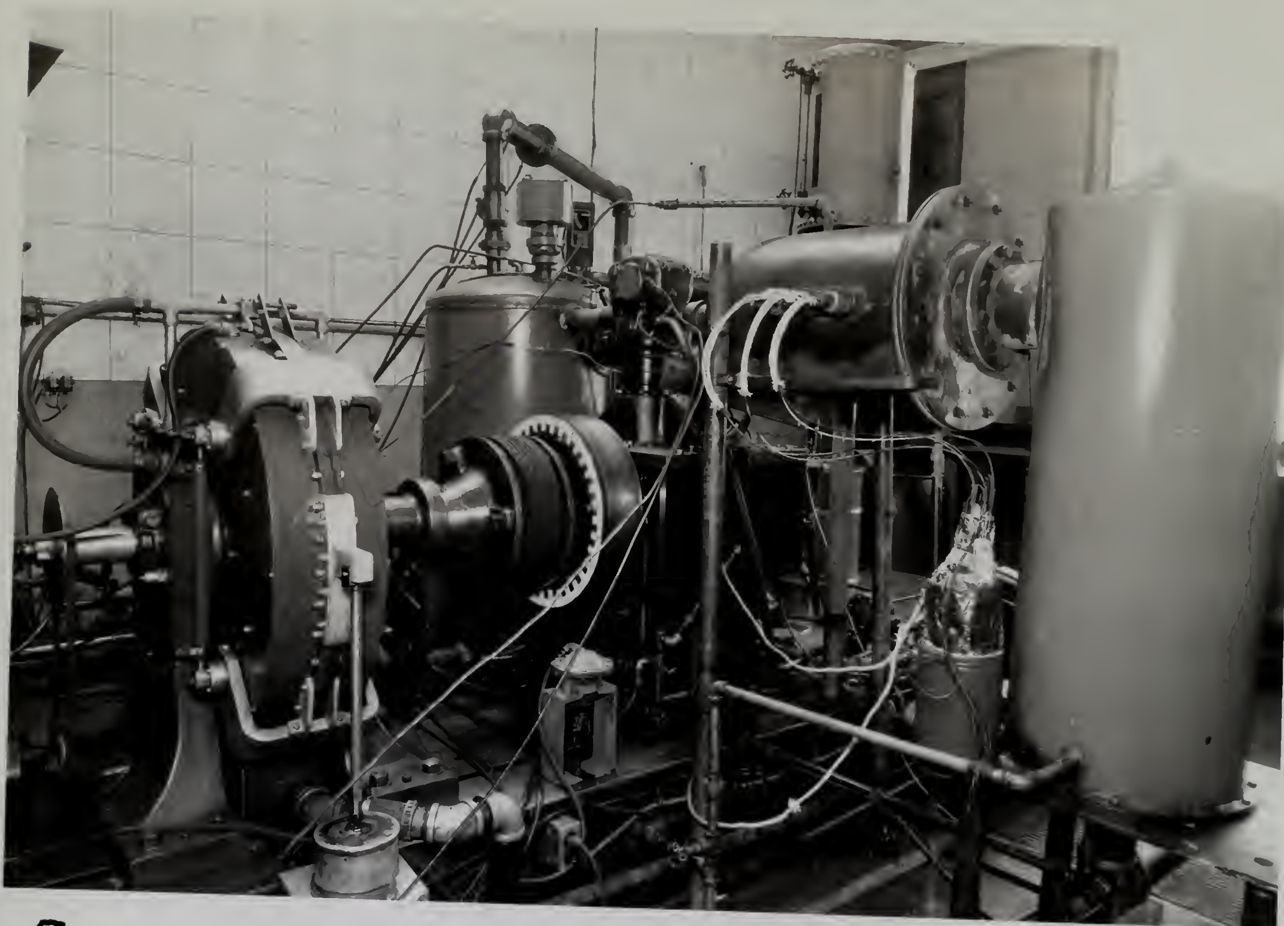


FIG. D

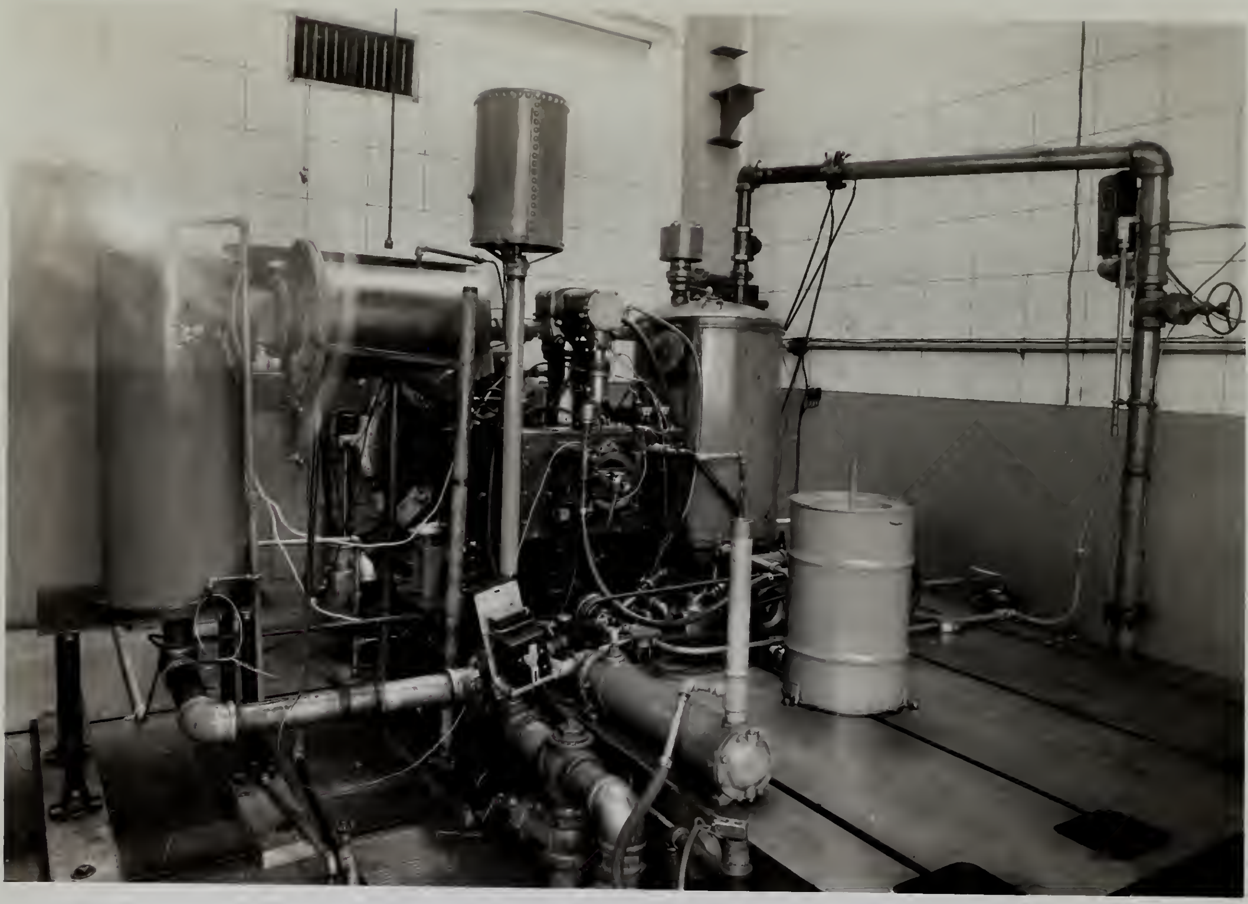
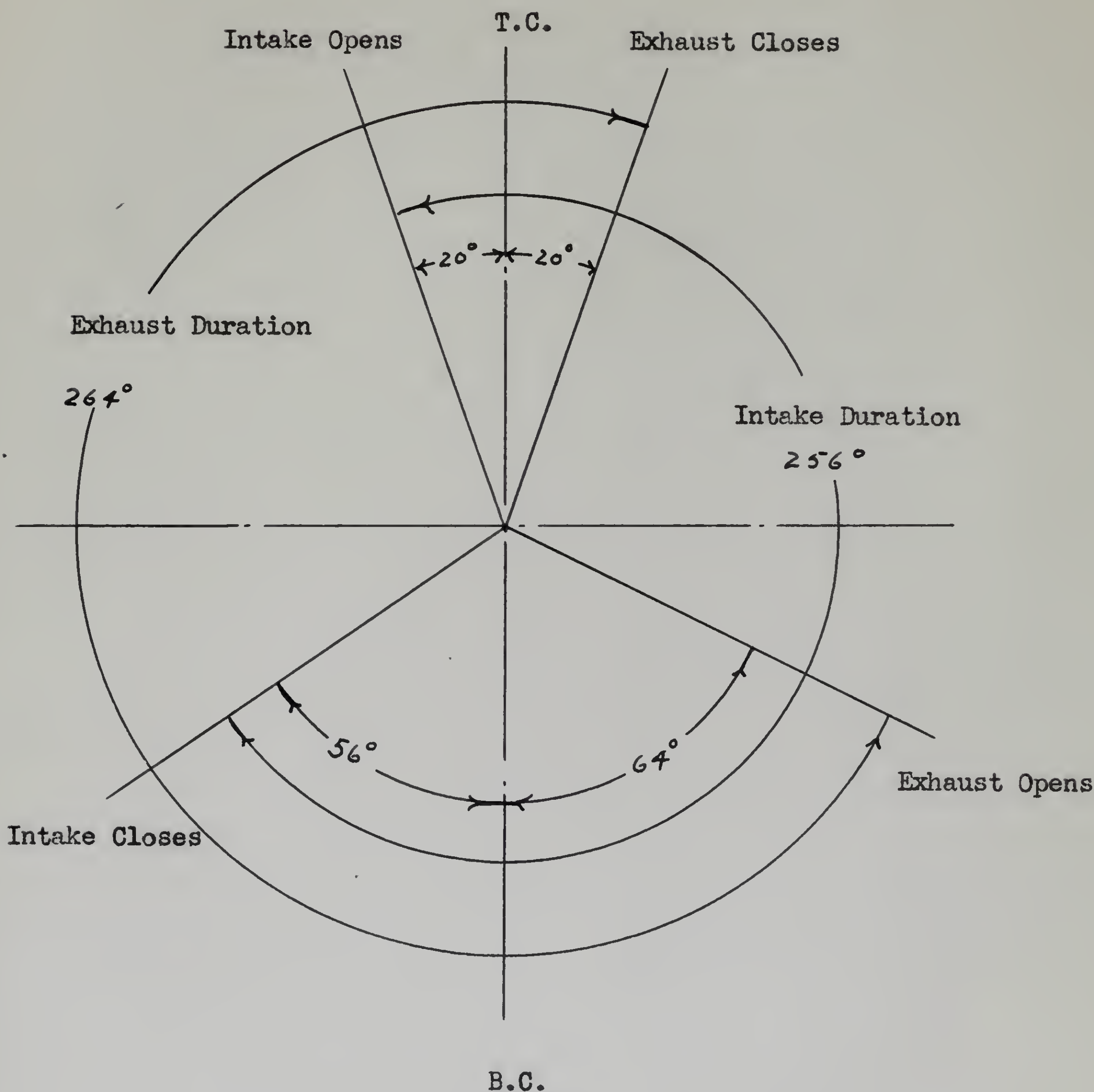


FIG. E

APPENDIX E



VALVE TIMING DIAGRAM

U.S.N.A.P.
89

Thesis 15398
K36 Kenna
The effect of high exhaust pressures on engine performance and the availability of energy in exhaust gases at high pressures.